

Multidisciplinary University Research Initiative

# **Space-Time Processing for Tactical Mobile Ad Hoc Networks**

Interim Report

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## **Abstract**

Recent developments in communication systems technology promise to greatly improve the performance of point-to-point communications for both commercial and tactical networks. These developments include the use of electronically steerable antenna arrays, space-time multiple input multiple output (MIMO) signal processing techniques, and improved techniques for error correction. In this project we will address the challenging question of how these technological developments can best be exploited in a tactical networking context, where signal interference and channel uncertainty issues have a tremendous impact on end-to-end system performance.

Tactical applications pose unique requirements for the network, including decentralized control to eliminate single points-of-failure, vulnerability to jamming and electronic warfare, and mission critical latency bounds for end-to-end data delivery. Moreover, a tactical network is generally composed of mobile nodes and the routing protocols must deal with a range of node mobilities and time varying channel conditions. Consequently this project is focused on the design of ad hoc networking architectures that utilize MIMO transmitters and receivers at each node. The goal of this program is to define the best way to utilize multiple transmit and receive antennas at each node to improve the robustness, capacity, and quality of service of the network.

## **1. Background**

The project team consists of fourteen faculty members from four campuses of the University of California (San Diego, Irvine, Santa Cruz, and Riverside); Brigham Young University, Provo, Utah; and McMaster University, Hamilton, Ontario, Canada. The individual faculty members were selected for specific areas of expertise that together spanned the wide ranging research concentration areas defined in the initial BAA for the topic area. The specified concentration areas spanned “the physics of RF propagation and signal processing; the electrical engineering of antenna array design and electronics; computer science of networking; and the mathematics of information and control theory”.

The specified objective of this MURI topic was to “create network protocols and signal processing algorithms necessary to implement adaptive beam steering and spatial channel reuse in mobile wireless communication networks with the specific objective of enabling reuse of radio channels to double network capacity and improve protection for military communications. The research should also result in the science that will allow for the decision of which spatial reuse technique to use (space-time coding (STC) or transmit beam forming), if any, based on topology and network load.

This report describes the specific accomplishments for the past year from August 1, 2006 through July 31, 2007. During this period the project team has written a total of 35 journal papers that have been published or accepted for publication, presented 65 conference papers and completed 22 manuscripts that have been submitted to peer reviewed journals. Also during this period, one additional PI, Michele Zorzi, was elected to Fellow of the IEEE, raising the number of PIs that are IEEE Fellows to eleven, with five elected since this project was initiated. In addition, Srikanth Krishnamurthy was elected to Senior Member of the IEEE. John Proakis received the inaugural Athanasios Papoulis award from the European Signal Processing Society for “Outstanding Contributions to Education in the Signal Processing Discipline”. Four PIs received best paper awards at IEEE Engineering Conferences: J.J. Garcia-Luna-Aceves at the International Symposium on Performance Evaluation of Computer and Telecommunication Systems and also at the IFIP Networking Conference; John Proakis and James Zeidler at the IEEE Personal, Indoor, and Mobile Radio Conference, and Michele Zorzi at the IEEE CAMAD Conference. Professor Zorzi also was nominated for the best paper at the ACM IWCMC and also for the IEEE Communication Society best tutorial paper award. Eight graduate students supported on this project received their Ph. D. degrees during the past year, raising the total number of students that have obtained their Ph.D. degrees to 12 since the project was initiated. A summary of the primary research advances made during the past year is provided below in Section 6. A more detailed description of the results can be obtained from the 122 published papers and submitted manuscripts referenced in Appendix 3.

## **2. Problem Definition**

A series of project meetings have been held at UCSD and UC, Irvine over the course of this project. The goal of these meetings was to first define a hierarchy of problems that require resolution and then outline the approaches to solve these problems so that robust and reliable mobile ad hoc networks can be developed for tactical applications. These group meetings have

led to joint work between PIs, joint publications, co-advising of graduate students, and numerous visits between subgroups of PIs to identify viable approaches for solving cross-layer networking problems.

The key research issue is to define how to best utilize multiple transmit and receive antennas at each node to improve the robustness, capacity, and quality of service for mobile tactical networks. Two baseline scenarios were selected initially to define the critical research issues for such a network. The primary difference in the two scenarios is the mobility of the nodes, with one scenario restricted to pedestrian velocities and the second including nodes moving at vehicular speeds. In both scenarios the number of nodes must be sufficiently large to provide a rich possibility of possible routing paths (nominally 30 to 100 nodes with up to four antennas per node in a typical scenario) and the range of node velocities sufficiently large to study topologies that must operate with a realistic range of temporal stabilities for the channel state information. The nodes may be shadowed from each other, creating network topologies where the nearest nodes are not necessarily connected to their neighbors and multi-hop routing is necessary to ensure network connectivity. Multi-casting and unicasting of wideband data and voice is a network requirement as is the necessity to reduce vulnerability to hostile interception.

The system considered is a wideband voice/data network operating at a nominal center frequency of 2.4 GHz. The channels considered include terrestrial models typical of rural and urban areas with both flat fading and frequency selective fading channels with a variable number of resolvable paths on each antenna. The practical limitations on antenna orientations associated with combat operations (e.g. operation close to the ground and non-ideal element location) are being evaluated. In both cases the impact of jamming and hostile intercept is being considered.

The possibility of hostile action to deny services or exploit the transmissions has an immediate impact on the choice of waveforms since a wideband spread spectrum waveform is required to mitigate jamming. In addition, the difficulty of achieving power control in ad hoc networks makes it desirable to consider alternatives to direct sequence Code-Division Multiple Access (CDMA). Consequently, in addition to determining the impact of power control errors for Direct Sequence CDMA in mobile ad hoc networks, variations of spread spectrum waveforms such as multicarrier CDMA and orthogonal frequency division multiplexing (OFDM) that utilize different approaches (such as frequency hopping) to spread the transmitted information will be considered.

Multicarrier waveforms will also provide spectrum flexibility by allowing the nodes to utilize whatever spectrum is available to increase network capacity and to avoid interferers. Time division and frequency division duplexing are being considered and the conditions for which scheduling can provide improved performance over contention based channel access protocols are being determined. The specific traffic models considered will include bursty and high density many-to-one, point-to-point and multicasting scenarios that incorporate multiple relays to provide end to end data/voice services. The ability of the network to smoothly transition from low data rate to high data rate operation will be evaluated. The general network architecture is a multi-hop ad hoc network without centralized control or single points of failure.

### 3. Research Goals

A primary objective is to develop new radio network technologies that provide an extended coverage range without the use of centralized control. Accordingly, a key research goal is to develop new routing and scheduling protocols that incorporate spatial information from the physical layer to improve performance at the higher layers of the network. Key metrics that will be used to evaluate the performance of the network include channel capacity in bits/sec/Hz and outage probability. Quality of service measures such as fairness, latency, bit-error rate, and energy consumption will also be determined. The robustness of the network and its associated outage probability will generally be considered as the most important metric for defining system performance in tactical applications.

This research is developing routing algorithms that support neighbor discovery and reliable end-to-end data delivery in a network that must smoothly transition between different data rates. The use of multi-input multi-output (MIMO) transmit/receive diversity can potentially provide significant gains in network performance but those gains come at the expense of a closed feedback loop between the physical, MAC and networking layers. The best approach to define this cross-layer processing is a critical research issue since the time scale for the feedback process must be compatible with the stability of the channel estimates.

The development of improved antenna, signal processing and coding technologies provide many forms of diversity to increase network capacity. The types of diversity available to the system designer include space, time, frequency, and polarization at the physical layer. In addition, network diversity can be achieved by exploiting multi-user diversity (through scheduling or routing) and cooperative diversity (by cooperative transmission). Diversity is critical to improve the reliability and minimize the need for retransmission and to reduce the latency in the network.

Exploitation of the available time, frequency and spatial diversity on a link allows the link capacity to be maximized, but for multi-user systems it also allows the multi-user interference to be minimized. Proper selection of waveforms, modulation, coding and spatial filtering is essential. In addition, cross layer optimization is required to exploit physical layer diversity at the network level. The chosen waveforms must be resistant to jamming and intercept and the antenna configurations adaptable to combat conditions. Multihop transmissions are required to overcome shadowing and allow network reconfigurability, and real time channel state information is required for time varying mobile channels. The time variability of the channel will depend strongly on the node velocities, since increasing velocities will introduce Doppler spreading that will limit the coherence bandwidths of the channel.

The goal of the cross layer design is to use feedback from the lower layers to discover and maintain appropriate routes and define the network topology and at the MAC layer to support scheduling based on interference zones and generated traffic. At the physical layer, adaptive antennas could be adjusted based on the needs of the network layer to provide feedback to higher layers to define the interference zones and minimize co-channel interference. In order to accomplish these goals it is essential to utilize the available diversity provided by the system parameters. The fundamental challenge of this project is to utilize combinations of physical and network layer diversity to maximize network capacity and robustness in a reliable fashion.

## 4. Research Issues

One key research issue is to determine the temporal variations of the CSI estimates at each node of the network as a function of the signal-to-noise ratio and Doppler dependence of various antenna processing and Space Time Coding (STC) algorithms. Optimizing network capacity will depend on where, when, and how accurately the CSI can be obtained. CSI may be available at the destination node only, source and destination node, or across the network. The time-scale of available CSI is especially important. It must be known whether knowledge about the channel can be expected to remain stable over a symbol interval, a packet interval, or over multiple packets.

The temporal stability of the CSI estimates is being evaluated and utilized to determine how frequently information must be exchanged between nodes for data delivery and also for the neighbor discovery process for various network topologies, node velocities, and channel conditions. Beamforming can increase the temporal stability of the network and potentially decrease the probability of hostile intercept, but this gain comes at the expense of requiring node tracking and the increased possibility of hidden nodes. Consequently the signaling architecture that is used to establish the locations of all the nodes and the data rates that are achievable on each link is a key research issue.

The contention based scheduling protocols that are currently used for ad hoc networks can provide a baseline for network performance, but the goal of this project is to provide enhanced performance through the use of beamforming and/or space-time coding. The work is focused on the development of distributed receiver oriented multiple access scheduling protocols for ad hoc networks with nodes that can use antenna elements to form multiple beams and maintain several independent communication links. The channel state conditions that are required to provide performance gain over contention based network protocols is a research issue that is being addressed in this project. A key research issue is the development of dynamic scheduling algorithms that exploit space-time coding and beam steered antennas to support unicast, multicast, and broadcast transmissions based on flow aware scheduling of transmissions.

The stability of the CSI estimates over the transmission paths is also dependent on the routing protocol selected and the manner the information is relayed between nodes. Consequently the determination of the type of feedback to employ, the number of bits allocated to the CSI feedback loops, and the number of nodes used to relay information between destinations are all important research issues. A number of open and closed loop feedback algorithms are being evaluated. A fundamental issue that will be addressed is the accuracy with which the channel gain matrix ( $H$ ) must be determined to support the MAC layer and routing protocols. One of the research issues that is being addressed is the development of hybrid space-time coding and beamforming architectures that optimize tradeoffs in performance and complexity with varying amounts of CSI. Multistage processes that would first locate the neighbors and then refine the  $H$  matrix computations will also be investigated. Other fundamental issues inherent to resolving the above questions are the role of local vs distributed information and relaying in the routing and scheduling protocols.



## **5. Role of Each Principal Investigator in Overall Research Objective**

The team was selected to provide some overlap in critical technology areas and collaboration between individual PIs is continuously being strengthened as the work progresses. Professors Garcia-Luna-Aceves, Krishnamurthy, Cruz, Javidi, Hua and Zorzi are addressing various aspects of the scheduling and routing protocols at the network and MAC layers.

Professor Garcia-Luna-Aceves's work is focused on developing MAC protocols that provide higher data rates through the use of STC, beamforming and any other available node location information from the physical layer. His research is evaluating the rates that CSI must be updated for both data delivery and neighbor discovery in various network topologies. Scheduling and routing protocols are being developed and evaluated to define their reliability as a function of the variations in the CSI estimates and refresh rates for channel conditions that include variable link quality over the available paths. During the past year his work has focused on defining the capacity of ad hoc networks that utilize multi-packet reception and developing MAC protocols that exploit multi-packet reception.

Professor Krishnamurthy is designing MAC and routing protocols that are tightly intertwined with what is possible at the physical layer, specifically to improve network performance using the reception of multiple simultaneous beams from a MIMO transceiver. Protocols that use directional transmissions for neighbor discovery with full and partial state CSI for data delivery are being evaluated. During the past year he has evaluated the MIMO diversity gain and also the MIMO spatial multiplexing gain in order to develop strategies to improve the end-to-end performance of mobile ad hoc networks (MANETs).

Professors Javidi, Krishnamurthy, and Zorzi are collaborating on providing a comparison of open loop protocols that exploit coding and end-to-end transmissions with forward error correction relative to closed loop techniques that require retransmissions. In addition they are designing a distributed MAC layer protocol that effectively schedules transmissions simultaneously in spite of the fact that the concurrent transmissions may also produce mutual interference. The use of geographical information in routing will also be evaluated. During the past year, Professor Javidi has studied the joint optimization of the MAC and physical layer to extend the notion of scheduling beyond the traditional operating point to include dynamic control of the physical layer using the available diversity and spatial multiplexing gains. Professor Zorzi is focusing on defining the best approach to integrate cross-layer information in the PHY, MAC and routing protocol layers. During the past year he has extended the integrated multiuser/MAC protocol developed in the previous year to include multihop scenarios and multi-user detection. Professor Zorzi has also developed MAC protocols that are designed to overcome the problems of deafness when directional antennas are used. Finally he has designed a distributed error control system for MIMO MANETs that is based on Hybrid Automatic Retransmission request (HARQ). This HARQ protocol gives greater adaptability to the channel conditions encountered in MIMO networks and the use of MIMO PHY layer to set up a cooperative protocol between nodes using a distributed HARQ scheme is examined.

Professor Hua is developing reliable relaying algorithms that exploit the MIMO channel information at each node and provide end-to-end data delivery in a large network by efficient multi-hop relaying. During the past year he has focused on issues in network throughput that consider the mutual interference between nodes in large networks. Mutual interference is essential to improve the network spectral efficiency, but can become a limiting factor to the throughput as the network becomes large. Professor Hua has investigated the various tradeoffs that arise.

Professors Swindlehurst, Jensen, Haykin and Zeidler are focusing on determining the accuracy and temporal stability of the CSI estimates for a MIMO based physical layer using a combination of analysis, simulation, and experimental measurements. Professor Swindlehurst is also developing algorithms for channel state estimation, prediction, and tracking and also on developing beamforming and coding algorithms that allow multiple users to communicate simultaneously with high throughput and minimal interference. Professor Jensen is utilizing his expertise in RF antenna design to assess MIMO system performance for realistic tactical environments and provide channel data models appropriate for realistic system simulation. Professors Jensen and Swindlehurst have worked jointly to obtain experimental validation of multiuser MIMO channel models using the BYU testbed. Professor Zeidler is collaborating with Professor Jensen on the analysis and validation of models that define the temporal stability of the channel state estimates. Professor Haykin, McMaster University, is also collaborating with Professors Swindlehurst, Jensen and Zeidler on channel tracking and the development of a MIMO receiver. Professor Haykin is funded separately by the Canadian government. He has met with Professors Zeidler, Swindlehurst and Jensen to coordinate research efforts.

During the past year Professor Swindlehurst has extended his previous work on performance bounds for channel estimation and started a new joint project with Professors Hua and Krishnamurthy at UC, Riverside on cooperative power allocation strategies in MIMO wireless networks. Professors Zeidler and Jensen have extended previous work on the use of channel distribution information (CDI) statistics from single user MIMO channels to multi-user MIMO channels with the goal of defining the stable subspaces of the MIMO channel that allow stable gain over time in a time-varying channel. The goal is to define techniques that provide stable gain for time frames of a packet length or more so that they can be more readily integrated with MAC and routing protocols. In addition, Professor Jensen has worked on refining the channel models for mobile MIMO nodes to more accurately capture the underlying physics of the RF propagation modes. In addition he has worked on optimal antenna design for mobile MIMO channels that includes the impact of imperfect terminations for the compact arrays that are employed on portable devices.

Professors Rao and Jafarkhani are evaluating open and closed loop feedback algorithms to provide CSI estimates to multiuser MIMO networks. Feedback based methods promise better utilization of the spectrum thereby supporting higher overall system throughput, and lower power communication suitable for low probability of detection (LPD) as well as design of simpler receiver structures. However, for these benefits to be realized in space-time ad hoc networks, many interesting questions have to be addressed. In order to support a wide range of node mobilities, Professor Rao has developed a flexible class of quantization techniques and evaluated their effectiveness and robustness. This study defines effective parameters to be fed

back, alternate efficient parameterization of the information being fed back, and the trade offs between complexity and performance. In connection with feedback issues there are also the associated problems of channel estimation and transceiver design to maximally exploit the feedback information. Professor Jafarkhani is designing STC structures that are flexible enough to be used in an ad hoc network and will consider the use of partial CSI and a combination of STC and beamforming. He will also evaluate meaningful measures of connectivity for ad hoc networks, such as symbol error rate and capacity using multiple antennas.

During the past year, Professor Rao has extended his previous work to include a capacity analysis of MIMO systems using limited feedback transmit precoding schemes and evaluating the performance of spatially correlated channels with estimation errors and feedback delay. These are two fundamentally different sources of performance error since channel estimation error can be reduced by increasing the pilot SNR, but delay errors require a fundamentally different approach. Professor Rao has evaluated the use of channel prediction to minimize the impact of feedback delay.

Professor Jafarkhani has investigated the impact of using noisy quantized feedback in MIMO systems. In order to combine the benefits of diversity/coding gain from space-time coding and the array gain from beamforming, it is necessary to quantify the degradations in performance that arise from various factors such as the bandwidth limitation of the channel and the delay and noise in the feedback link. He has extended his previous work on space-time block codes to provide more robustness to these effects and developed joint source-channel coding techniques that allow rate distortion techniques to be applied to the design so that the distortion measures can be selected based on the type of information that is to be transmitted, (i.e. the best design criterion may be different for image, data or voice signals).

Professors Milstein, Proakis, and Zeidler are evaluating a number of signal and waveform issues involving the stability and accuracy of the CSI estimates from mobile multi-user MIMO transceivers. Professor Milstein is evaluating the best modulation approaches for the underlying waveforms and defining the tradeoffs between diversity and channel estimation errors for alternative multicarrier CDMA waveforms. He is also addressing the problem of optimizing the cross-layer interactions in a mobile tactical environment, emphasizing spatial processing wherever feasible and defining the channel conditions and delay constraints that are required to support scheduling in an ad hoc network. Professor Proakis is developing signal design and equalization approaches for a mobile multiuser MIMO network and the use of CSI estimates in the physical and network layer optimization. Professor Zeidler is also evaluating the reliability of CSI information for frequency-hopped spread spectrum waveforms in a mobile multi-user MIMO network.

During the past year, Professor Milstein has extended his analysis of spread and unspread multicarrier code division multiple access systems (MC CDMA) and developed a multicode MIMO technique to achieve high data rates in mobile ad hoc networks. In addition, he has considered the design of a cross-layer multi-user resource allocation framework using a cognitive radio perspective by which the optimal power and bit allocations, as well as the optimal subcarrier assignments can be determined. He has also investigated the use of cooperative node selection in a cooperative MIMO communications that allows virtual MIMO performance to be

achieved in a resource constrained environment using multiple neighbors, each equipped with a single antenna. Professors Proakis and Milstein have also collaborated on signal design and channel equalization for MIMO ad hoc networks. They have developed transmitter precoding techniques that are effective in multi-user networks.

Professor Zeidler has evaluated the use of frequency-hopped CDMA (FH-CDMA) waveforms for MIMO systems. Such waveforms achieve spatial diversity by differential unitary space-time coding and time/frequency diversity by coding/interleaving. A novel receiver structure was developed to perform joint estimation-demodulation-decoding and is shown to be robust in the presence of jamming, multi-user interference and power control errors. The optimization of the transmission range for this system in an ad hoc network was evaluated using a slotted-ALOHA MAC protocol. The concept of information efficiency was utilized to evaluate the best transmission range as a function of the modulation and coding scheme, the receiver parameters the channel statistics and shadowing characteristics. Professors Proakis and Zeidler also collaborated on the use of a combination of frequency hopping and convolutional coding to mitigate multiple access interference in an ad hoc network. This work develops network performance metrics such as the network throughput, the information efficiency and the transmission capacity to evaluate the effectiveness of various MIMO signaling techniques.

## 6.0 Scientific Progress and Accomplishments

### 6.1 Many-to-Many Communication and Opportunistic Virtual MIMO in Ad Hoc Networks

**PI: J.J. Garcia-Luna-Aceves**

**GSRs: Xin Wang, Walter Wang**

#### SUMMARY OF ACCOMPLISHMENTS

During this reporting period, we have obtained results in following two areas related to the theory and design of communication protocols for ad hoc networks with MIMO nodes:

1. Capacity of ad hoc networks with multi-packet reception
2. Protocols for medium access control exploiting multi-packet reception

#### Capacity Analysis of Ad Hoc Networks

The communication protocols used today in ad hoc networks are based on a one-to-one communication paradigm in which a given receiver is able to decode at most one transmission correctly and transmitters and receivers orchestrate transmissions trying to offer at most one transmission around a receiver at any given time. The main objective of this one-to-one communication approach is the avoidance of multiple access interference (MAI). Unfortunately, as the work by Gupta and Kumar has shown [1], the per source-destination throughput in a connected random wireless ad hoc network of  $n$  nodes adhering to such a communication paradigm scales as  $\Theta(1/\sqrt{n \log(n)})$  for multi-pair unicast applications. This result was obtained under the protocol model [1], in which a transmission carries a single packet, and a given transmission is successful at a receiver only if the transmitter is within the reception range of the receiver and no other node transmits within a distance equal to  $(1 + \Delta)$  times the reception range, where  $\Delta$  is a function of the physical layer. Intuitively, the sharp decrease in capacity experienced as the number of nodes increases in an ad hoc network using point-to-point communication can be explained in the protocol model by the fact that a single successful transmission occupies a circumference given by the reception radius of the receiver, and this area is a function of the minimum radius needed for the network to be connected. Hence, as nodes are added, a smaller percentage of nodes are free to become a successful transmitter. Clearly, without exploiting node mobility [2,3], the only two possible approaches to increase the order capacity of an ad hoc network consist of (a) increasing the amount of information a transmitting node relays in each transmission, or (b) enabling a receiver to decode multiple concurrent transmissions within its reception radius. Work has been carried out in both fronts.

Recently, Ahlswede et al. introduced the concept of network coding (NC) [4], which allows nodes to conduct processing and combining on received packets before forwarding them. They proved that the max-flow min-cut throughput can be achieved for single source multicast applications in a directed graph in which there are no restrictions on when a node can send and

receive information. This result has motivated a large number of researchers to investigate how to increase the throughput capacity of ad hoc networks using NC (e.g., [5]). However, Liu et al. [6] recently showed that NC cannot increase the throughput order of wireless ad hoc networks for multi-pair unicast applications when nodes are half-duplex. This result is related to the theorem given by Li and Li [7], who proved that NC has no throughput gain for unicast and broadcast applications, and can provide a throughput capacity that is at most twice that of an undirected graph with no NC.

Ghez et al. [8] and Mergen and Tong [9] provided a framework for many-to-one communication. In this context, multiple nodes cooperate to transmit their packets simultaneously to a single node using multi-user detection (MUD), directional antennas (DA), or multiple input multiple output (MIMO) techniques (e.g., [10,11]). The receiver node utilizes MUD and successive interference cancellation (SIC) to decode multiple packets. Toumpis and Goldsmith [12] have shown that the capacity regions for ad hoc networks are significantly increased when multiple access schemes are combined with spatial reuse (i.e., multiple simultaneous transmissions), multi-hop routing (i.e., packet relaying), and SIC.

Over the past year, we have analyzed the capacity of ad hoc networks under the protocol model and the physical model when MPR is used at each network node [13,14]. In the original protocol model assumed by Gupta and Kumar [1], a wireless network is represented with an undirected graph (bidirectional links) such that two nodes  $X_i$  and  $X_j$  can communicate directly only if they are connected with an edge. These graph models have traditionally been used assuming a collision channel assumption [1], which we also denote by one-to-one communication assumption. That is, two nodes can communicate directly if they are within a distance  $d(n)$ , and the transmission from node  $X_i$  to node  $X_j$  is successful only if there is no other transmitter within distance  $(1+\Delta)d(n)$  to node  $X_j$ . This inherently implies that the disks of different concurrent receivers with radius  $d(n)$  are disjoint. Applying the same protocol model to wireless networks with MPR capability means that nodes are able to receive successfully multiple packets concurrently, as long as the transmitters are within a radius of  $r(n)$  from the receiver and all other transmitting nodes have a distance larger than  $(1+\Delta)r(n)$ . The key difference is that MPR allows the receiver node to receive multiple packets from different nodes within its disk of radius  $r(n)$  simultaneously.

In the physical model [1], a successful communication occurs if  $SINR \geq \beta$ , where

$$SINR = \frac{P_{ij}(t)g_{ij}(t)}{BN_0 + \sum_{k \neq i, k \in A} P_{kj}g_{kj} + \sum_{t \neq i, t \notin A} P_{tj}g_{tj}}$$

with MPR, each receiving node is able to decode the transmissions of all the nodes transmitting within its receiving range of distance  $A$ , and any transmission outside that range is considered interference. In the equation above,  $P_{ij}$  is the transmit power of the node  $i$  with closest distance to the receiver  $j$ ;  $P_{kj}$  is the transmit power of a node other than  $i$  within the receiver range, which constitutes constructive interference (second term in the denominator); and  $P_{tj}$  is the transmit power of node  $t$  outside the receiver range, \footnote{Note that for the MPR model, we need to define receiver range as opposed to transmission range for point-to-point communication, which is considered a destructive interference (third term in the denominator)}.

Using the protocol model, we have demonstrated that the per source-destination throughput of a random wireless ad hoc network of three dimensions (or 3-D network) in which nodes utilize MPR is bounded by  $\Theta(r(n))$  (upper and lower bounds) with high probability when the protocol model is used, where  $r(n)$  is the reception range of receiver. This result is quite remarkable! Given that  $r(n) \geq \Theta(\sqrt[3]{\log(n)/n})$  in order to ensure that a random ad hoc network is connected, our result implies that a gain in the order capacity equal to  $\Theta(\log(n))$  can be attained by exploiting MPR in network nodes compared to the capacity that can be achieved with simple multihop routing [1] (i.e., one-to-one communication) or NC [6]. This is in stark contrast to all existing results in ad hoc networks assuming point-to-point communications! It states that *increasing* the communication range  $r(n)$  actually *increases* the capacity of an ad hoc network. Intuitively, the reason for this is that, given that all receivers are endowed with MPR, MAI around any receiver becomes useful information and no longer decreases the capacity. Clearly, the restrictions in choosing the communication range among nodes are: (a) the need to maintain connectivity in the network, which provides a lower bound on  $r(n)$ ; and (b) the energy spent per transmission, the transmitter complexity, and the decoding complexity of the nodes in the network, which provides a practical upper bound on  $r(n)$ .

We have also shown that, under the protocol model, MPR provides a gain in the order throughput compared to NC in an ad hoc network in which optimum routing is known to all sources and a combination of multi-pair unicasting and a single-source multicasting to a small group take place, MPR provides a gain in the order capacity of the network compared to NC. Intuitively, this result can be explained by noticing that the percentage of multicast traffic becomes smaller compared to the multi-pair unicasts as the number of nodes increases, and then applying the results by Liu et al. [6] and our result on the capacity with MPR.

Using the physical model, we have also shown that a gain of  $\Theta(\log(\log(n)))$  can be achieved in a two-dimensional random network compared with the capacity result by Gupta and Kumar [1]. The key significance of these results is that, with MPR, the ability of ad hoc networks to scale is no longer limited by MAI. We note that, while our results to date are very promising, they are limited mostly to the case of multiple unicast applications. Over the next year, we will investigate the capacity of ad hoc networks for multicast and broadcast applications, and study what capacity gains can be attained by means MPR and NC.

### **MPR-oriented MAC Protocols**

Our results on the capacity of ad hoc networks with MPR show that MPR can have a tremendous impact on the performance of future ad hoc networks, because it enables the protocol architectures of such networks to be based on many-to-many communication (i.e., the orchestration among transmitters and receivers in order to exploit the MPR capabilities offered at the physical layer). However, turning these theoretical results into practice represents a big challenge. In practice, receivers can decode only a finite number of concurrent transmissions, rather than all the transmission that occur within their reception range. Therefore, trade-offs are needed between the added efficiency attained by means of concurrent transmissions, and the added cost incurred by the complexity of the receivers that must process such transmissions. Furthermore, the communication protocols used to date in ad hoc networks have been designed

to avoid MAI, and are derivatives of protocols and architectures originally designed for wired networks based on point-to-point links. For example, today's popular IEEE 802.11 DCF can be viewed as attempting to emulate "Ethernets in the sky" in that at most one transmission is allowed to reach a receiver, and senders are forced to back off in the presence of MAI. Similarly, the IETF MANET routing protocols are based on the assumption that packets are to be forwarded along single paths, and they work independently of the channel access method, even though it is not true that routing in MANETs occurs over a pre-existing network topology and the transmission over one link does not impact the transmissions over other links, as it can be done in a wired network. Therefore, for MPR to really help ad hoc networks scale (i.e., an increase in capacity over today's approaches in the order of the degree of nodes in the network), the protocols used in such networks have to be redesigned from the ground up to embrace, not combat, MAI.

During the past year, we have taken the first steps in the redesign of protocols stacks of MANETs to take advantage of many-to-many communication. We developed a new protocol for collision-free channel access in ad hoc networks called Election based Hybrid Channel Access (EHCA) [15]. EHCA is based on bids made by nodes for slots within the context of probabilistic channel access. Winners of the bids for a given slot are determined as a result of a fair election of the bids for that slot. Nodes attempt to acquire varying number of slots depending on their traffic requirements. Nodes transmit their schedule information once in each frame prior to the data packet transmission in the slots acquired by them. Schedule information for a given slot is corrected based on the same fair election by the nodes that hear the schedule information. Discrete-event simulations were used to compare EHCA with other MAC protocols, with the results showing that it provides better throughput and much lower end-to-end delay at low and high traffic loads. The traffic adaptive nature of EHCA allows for the performance of EHCA to be largely independent of the network load.

We introduced the distributed CHannel Access scheduling using virtual MIMO Protocol (CHAMP) [167,17]. In CHAMP, nodes build a channel schedule in a distributed fashion to utilize the spatial multiplexing gain of virtual MIMO links. CHAMP also introduces a cooperative relay strategy to fully utilize the available degrees of freedom of virtual antenna arrays. We analyzed the single-hop saturation throughput of CHAMP and evaluated its multi-hop performance through simulation. The results of our analysis show that CHAMP can achieve better performance than a contention-based MAC protocol using MIMO links.

Our results to date on protocol design exploiting virtual MIMO are very encouraging, but have two main limitations. First, we have not characterized the physical layer in detail. Second, we have not considered the interaction of the MAC and network layers. During the following year, we will seek answers to the following questions related to MAC and routing design in the context of many-to-many communication enabled by MPR.

For channel access control, we will address: (a) The coordination among senders and receivers under varying degrees of mobility, such that the receivers can provide feedback to senders on channel state information (CSI). (b) The efficient use of dynamic channel division (i.e., time division, frequency division, and space division) to divide the MAI around receivers, such that the probability of successful decoding by any one receiver is increased. (c) The incorporation of



network-level information in the decisions made for elections and reservations (i.e., the integration of routing and scheduling). (d) The interaction between elections and reservations.

Routing and forwarding in the context of many-to-many communication call for the exploitation of concurrency at the link level and redundancy at the network level, because the MAI caused by data and control packets can be managed and exploited. Hence, a route to a destination should be a "multipath" consisting of multiple paths that need not be edge or node disjoint, multi-copy forwarding can be used to disseminate data over a multipath, periodic updates should be sent so that multiple concurrent updates reach the neighbors of transmitters at the same time, multicasting can be attained over "concurrency" meshes in which all multicast transmissions are useful information, and "feasible concurrency relays" can replace today's multi-point relays to disseminate control signaling in a way that a relay is feasible if it can transmit concurrently with other nodes to intended neighbors.

We believe that embedding the signaling needed to establish multipath routing with the signaling needed to establish transmission schedules is the main routing challenge for many-to-many communication. Important problems associated with this challenge are: (a) How should nodes elect and reserve time slots for the signaling required for unicasting and multicasting that exploit concurrency and redundancy? (b) How should feasible concurrency relays be selected to maximize the reliability of signaling while making efficient use of link-level concurrency? (c) How should the "width" of the multipaths (number of neighbors each node uses as next hops to a destination) be controlled depending on demand? and (d) How should reliability be increased or average delay or jitter be decreased by means of multi-copy forwarding over multipaths?

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## **6.2 Scheduling and Optimal Diversity for MIMO MAC with Bursty Delay-sensitive Traffic**

**PI: Tara Javidi**

### **SUMMARY OF ACCOMPLISHMENTS**

We studied the joint optimization of the MAC layer and the physical layer. To do so, we extended the notion of scheduling beyond the traditional time/frequency scheduling, to include any (possibly dynamic) control of PHY operation point (POP) such as diversity and multiplexing gains. This enables us to bring together, for the first time, scheduler's statistical multiplexing gain at the MAC layer with those gains offered at the PHY layer. We also investigate the optimal cooperation strategy from an end-end delay perspective.

#### **Prior Research on Optimal Operating Point in Point-Point MIMO Communication**

In the first two years of the project, we addressed this question at a high SNR regime, where seminal work by Tse, Viswanath, and Zheng [1] has characterized the fundamental tradeoff between the first three types of gains. In this context, our work has been to answer the question posed by Holliday and Goldsmith in [2] : “given the diversity-multiplexing region, where should one choose to operate?” In our work, we answer the same question in a QoS aware, cross-layer, delay-sensitive context with bursty arrival traffic (e.g. [3]–[5]). In particular, we consider a cross-layer queue-channel optimization problem for bursty transmission over MIMO point-point channel (MIMO P2P) [3] or a cooperative MIMO networks [5] . The end-to-end performance metric of interest is the total bit loss probability, where loss can be due to either delay violation or decoding errors in the MIMO channel. The main contribution of our previous work is a methodology for characterizing the optimal diversity gain for a MIMO channel with a given SNR and description of the bursty traffic sources. In this setting where errors are attributed to atypical bursts of information (delay violation) as well as atypical fading realizations (channel outage), a tradeoff is presented between the queue service responsiveness and the diversity gain.

Cooperation among users in a wireless network can substantially improve the reliability of communication [8]. These improvements relate to encoding across space and they fully appear only after some minimum finite amount of time-averaging. As a result, when the bit-arrival process is stochastic and bursty, and when the bits are limited by a strict delay requirement, this required temporal averaging and the corresponding reduction in queue responsiveness, results in an increase of the probability of error due to delay violation.

Previously, we explored this above tradeoff, i.e., we explore the relation between mitigating for channel errors and mitigating for delay-violations of delay-sensitive and bursty information both in a point-to-point MIMO setting as well as the cooperative network setting.

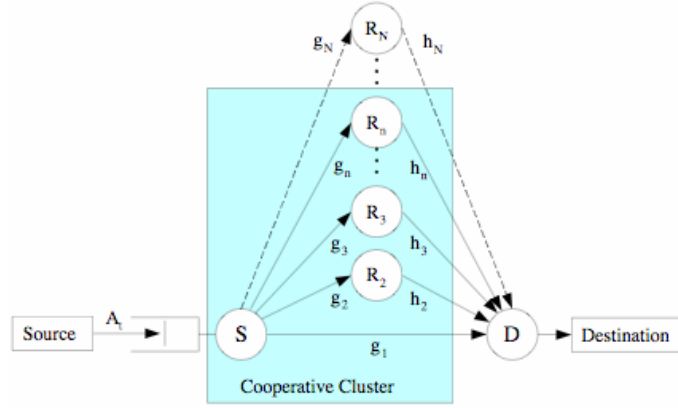


Figure 1. In a cooperative wireless setting, the messages of each user (indicated as Source A) is transmitted via the help from other users (indicated as Relays).

In a cooperative setting and in the presence of fading, network users exchange and transmit functions of each others' signals in a manner that emulates multiple-input, multiple-output (MIMO) communications as shown in Fig.1. In the setting where errors are solely due to channel (deterministic and non-bursty bit-arrival process and/or no delay limitations), cooperative diversity techniques reduce the probability of decoding error by diversifying resources and exploiting fading independence across nodes. In this same setting, error performance relates to, among other things, the transmission's rate-to-power ratio and to the average number of fading paths associated with each bit of information. The above relations were nicely captured, using large deviation techniques [9] by the concept of the diversity-multiplexing gain tradeoff (DMT) [1], which will be recalled later in the context of cooperative networks. DMT analysis offers the important result that in the outage-limited quasi-static setting of fixed fading, the asymptotically optimal error performance can be achieved with coding over some finite time duration [1] as long as this time duration is larger than some minimum encoding time which is usually a function of the number of transmitting nodes [6].

However, when cooperation aims to assist the communication of stochastic and bursty information with delay limitations, then this spatiotemporal averaging, which mitigates the stochastic nature of the channel, gets in the way of queue responsiveness, resulting in slower emptying of the queue, and in more bits violating the delay limitation placed by the receiving application. In our previous work [3], we explored this tradeoff in the relation between mitigating for channel errors and mitigating for delay-violations of delay-sensitive and bursty information. More specifically, we analyzed the asymptotic probability of overall bit loss due to both transmission error as well as delay-violation. Under the assumption of asymptotically high scaling of the signal-to-noise ratio (SNR), fixed average packet size, and fixed system loading, we provide an analytical expression for the overall probability of error due to both the channel and delay. This expression was then used to quantify the tradeoff between performance enhancement due to diversity gain and performance degradation due to the reduced responsiveness of the queue. We presented this responsiveness-diversity-multiplexing tradeoff (RDMT), specifically, for the orthogonal symmetric amplify-and-forward (OAF) [7] channel, with minimum encoding delay and for the compound-Poisson bit-arrival process. This tradeoff is in form of a simple expression between channel and application related parameters such as

SNR, Rayleigh fading statistics, the rate-to-power ratio, the compound Poisson parameters, and the delay limitation. As a practical consequence, the tradeoff tells us how to pick the information rate and cluster size of cooperative users, in order to balance the effects of channel atypicality (outage) and burstiness atypicality.

In summary, our previous work investigates the asymptotic error performance of outage-limited communications in cooperative wireless relay networks, with fading that is quasi-static, with an information-arrival process that is stochastic and bursty, and with bits that have a strictly limited lifespan. Employing large-deviation techniques, we analyze the probability of bit error where such errors are due to both erroneous decoding as well as due to delay violation. We derive a tradeoff between, on one hand, the optimal negative SNR exponent of the total probability of error, and on the other hand, the ratio of the average bit-arrival rate to the ergodic capacity of the channel. This allows us to arrive at the overall error exponent with various assumptions on the clustering size. Figure 2 shows the result for the case of the orthogonal amplify-and-forward protocol, constant system loading, many flows and asymptotically high values of SNR, where  $D$  represents the delay bound, and  $\mu$  represents the average packet size.

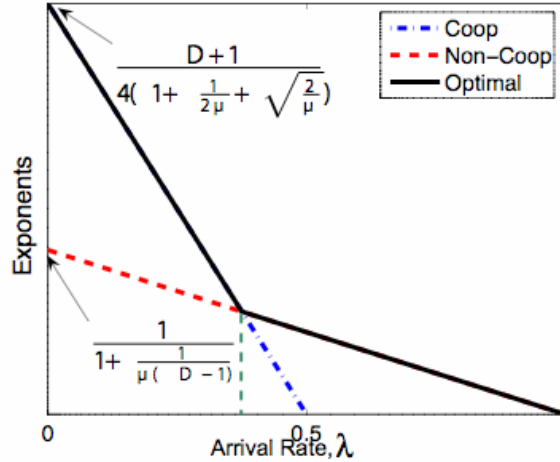


Figure 2. The exponents of overall probability of error for the case of optimal cooperation, and no-cooperation versus the arrival rate.

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### **6.3 Cross Layer Design for Enabling and Exploiting Space-Time Communications in Ad Hoc Networks**

**PI: Srikanth Krishnamurthy**

**GSRs: Gentian Jakllari, Ece Gelal, Konstantinos Pelechrinis,**

#### **SUMMARY OF ACCOMPLISHMENTS**

During this period we have primarily focused on the achievable improvements in the end-to-end performance of MANETs by leveraging the gains offered by MIMO systems at the physical layer. We have carried out two independent research projects one on the diversity and the other on spatial multiplexing gains achievable with MIMO systems, respectively. In the following we briefly summarize our progress with both projects.

1. Studying MIMO Diversity Gain: Our goal is to examine the impact of this gain at the higher layers. In particular we focus on the trade-offs in terms of an increase in range versus an increase in rate. We generate practical scenarios wherein the environmental effects are modeled in detail; we compare end-to-end network performance with various possibilities that provide different rate versus range trade-offs. Our initial results with some simple models for the PHY layer have been published in Asilomar Conference on Signals and Systems. We have improved our PHY layer accuracy; currently we are

testing our new model with different routing metrics to compare how end-to-end performance differs with the two physical layer models.

2. **Studying MIMO Spatial Multiplexing Gain:** We have designed a SIMO communication model in the ad hoc network where each node transmits using one antenna and a receiver can detect and decode up to  $K$  ( $K$ : number of antennas on a node) spatially multiplexed signals transmitted from multiple nodes. Our goal is to form a framework that activates different sets of communication links simultaneously, such that the activation of all links can be done within as small a time-period as possible, with the requirement that the links that are active together, are provide packet delivery at the receivers with high probability. We have shown that this problem is NP- hard; we have outlined the structure of our solution; currently we are working on its detailed design.

### 1. Exploring the tradeoffs between the High Rate and the High SNR Communications with Diversity gain

The use of space-time communications provides a way of exploiting the uncorrelated fades among antenna pairs when nodes in the network are equipped with multiple antennas. The diversity gain thus achieved causes an increase in the post-reception SNR (signal-to-noise ratio) at the receiver end; the higher SNR automatically results in lower bit errors in the decoding process. The increase in reliability can be exploited either for an increase in the transmission bit rate, or for enabling successful decoding at farther receivers. We refer to these possibilities as the “increase in rate” and “increase in range”, respectively.

The **increase in rate** is achieved by using the modulation schemes with a denser constellation; the reduction in the variance in the received energy per bit (with the diversity gain) still enables correct demodulation at the receiver with high probability. The **increase in range** is achieved, as the enhanced SNR can accommodate the channel degradation (a combination of path loss and multi-path fading effects) that is experienced by the farther receivers; in other words, with diversity decoding is possible at farther distances with lower bit errors than with SISO communications. We study the end-to-end performance in mobile ad hoc networks (MANETs) when different space-time codes are used at the physical layer for creating various levels of increase in range and increase in rate.

#### A. Preliminary Simplistic Diversity Gain Model

In our initial approach we modeled MIMO diversity gain as a leading to a *constant* decrease in the SINR requirement for successfully decoding the received symbols. In other words, the asymptotic diversity gain was assumed to be achievable with all packet receptions. All packet exchanges are preceded by the pilot tones; communication between a node pair enjoys diversity gain if the receiver detected the corresponding pilot tones and obtained the corresponding CSI (channel state information). We employ 4x1 orthogonal space-time communications as specified in [1]; using these codes the diversity gain for a BER of  $10^{-3}$  is 15 dB.

We compute the achievable increase in range with 15dB of diversity gain based on the model in [2], by the following formula, which derives the new achievable communication range with MIMO, with a particular diversity gain, relative to the SISO range:

$$R_{DG} = R_{SISO} * 10^{\text{DiversityGain}/10\alpha} \quad (1)$$

In (1) above,  $R_{SISO}$  and  $R_{DG}$  are the SISO and MIMO communication ranges respectively; and  $\alpha$  is the path loss exponent of the wireless channel.

We determine the increase in rate based on the modulation scheme used. Symbols must have a higher SNR for successful demodulation, when more aggressive schemes (i.e., more bits are sent per symbol) are used. When diversity gain is used for an increase in data rate, a percentage of the potential diversity gain is spent for supporting this rate (the percentage depends on the constellation of the modulation scheme; we incorporate these values from [2]); and the remaining diversity gain will be used to support an increase in range. In Table 1, we present the data rate and communication range values that are associated with each scheme.

Modulation Scheme	Diversity Gain for Increase in Range	New Range	Diversity Gain for Increase in Rate	New Rate
SISO	0 dB	0 dB	1 unit	1 unit
BPSK	15 dB	1 unit	0 dB	~3.1 units
QPSK	13 dB	2 units	2 dB	~2.7 units
8-PSK	10 dB	3 units	5 dB	~2.1 units
16-PSK	5 dB	4 units	10 dB	~1.4 units

**Table 1 : Achievable Data Rates and Communication Ranges Achievable with MIMO Diversity Gain for Various Modulation Schemes**

We used AODV ad hoc routing protocol and IEEE 802.11g protocol at the MAC layer. We tested the end-to-end network performance for varying traffic load, node densities and node speeds; for each parameter and we compare the behavior of each scheme above.

This work has appeared in Asilomar Conference on Signals and Systems. We explain our results and discuss how they compare with the observations on our new model (described next), later in the report.

## B. Accurately Characterizing the Diversity Gain

The diversity gain is due to the exploitation of multiple independently fading channels between a communicating node pair. The receiver decodes the space-time block-coded signal by using the channel knowledge it acquired via the training sequences. However, if the energy per symbol in the received signal is very low (or the momentary fades in the channel obstructed the correct training of the channel information at the receiver), the receiving node may not be able to decode this symbol; thus the potential diversity gain cannot be exploited for this communication. To reflect this effect in our new model, we compute the amount of diversity gain based on the post-reception SNR of the transmitted symbols (as opposed to using a fixed value that is equal to the asymptotic gain).



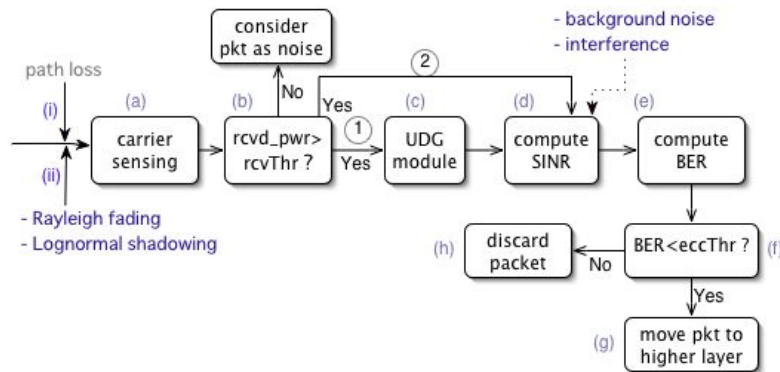
We use the simulated values for the required SNR for a given BER using orthogonal space-time block codes (OSTBCs), from [3]. In particular [3] provides the required for data rates of 1 bps/Hz (BPSK), 2 bps/Hz (QPSK) and 3 bps/Hz (8-PSK); the modulation scheme-OSTBC tuples that can be used for each data rate, are also provided for each data rate. For a fixed data rate (e.g. 1 bps/Hz), the diversity gain for a post-reception SNR of  $\chi$  dB is retrieved from the corresponding SNR-BER table as follows: we lookup the BER  $\beta$  that corresponds to  $\chi$  dB using OSTBC on a 4x1 MISO link (with appropriate modulation that supports the data rate in use, e.g. BPSK or rate 1/2 QPSK for 1 bps/Hz). We then lookup the SNR value  $\chi'$  that would be needed to achieve the same BER using an appropriate modulation scheme (e.g. BPSK at the 1 bps/Hz data rate) for a SISO communication.

*Diversity gain is modeled to have a value of the difference along the horizontal line between the two SNR curves (with/without OSTBC) at the BER value of  $\beta$ , i.e. diversity gain equals  $\chi' - \chi$ .*

This model significantly differs from the previous model (used in our initial work reported in the paper at Asilomar). Most importantly, the diversity gain does not have a fixed value for all receivers; it differs based on the SNR when the transmitted signal is detected.

(i) Increase in range is not fixed: We do not “compute” the “range” achievable with this diversity gain. With a more accurate channel model (that incorporates Rayleigh fading and lognormal shadowing effects on the signals transmitted), the simulator follows the stages showed in Figure 3 below; it computes the number of bit errors in a received packet, which determines whether a successful reception is possible. In this model there is no concept of a constant distance at which successful reception is certain, and beyond which all nodes drop the detected packet.

(ii) Increase in rate is not a fixed value: We no longer assume that the SNR that is needed to support an increased data rate has the same value for all receivers (similar to the approach in exploiting increase in range). Using the tables that present the SNR values for achieving a given BER value using 4x1-MISO and SISO communications at 1bps/Hz, 2bps/Hz and 3bps/Hz from [3], we determine the corresponding values based on the receiver’s post-reception symbol SINR.

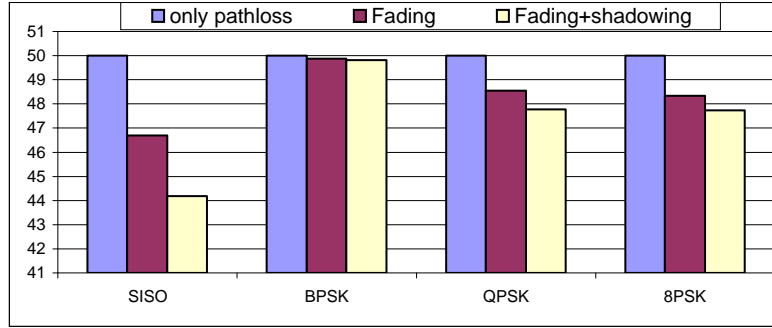


**Figure 3: The model for packet reception at the receiver, for both the initial and the improved models**

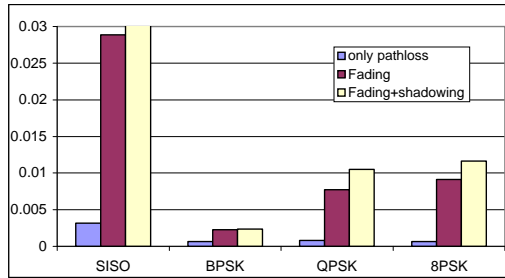
Our initial model did not have the channel effects in (ii) prior to stage (a) in Figure 3. In addition, it followed the route over link (1) between stages (b) and (d). The “UDG module” here refers to

the unit disk graph model that was imposed, by pre-computing the communication range in Equation (1), and ignoring the possible decoding of a packet at the nodes beyond this range. With our new model, we have employed DSR as the ad hoc routing protocol. DSR seems to interact better with routing metrics other than only the hop count.

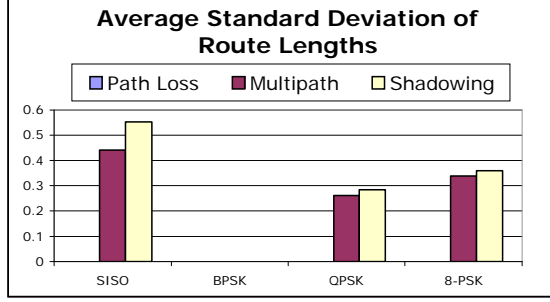
Figure 4 depicts the end-to-end throughput in a 50-node network with 5 flows, where each flow generates 10 packets/sec. Note that when there is only path loss, all generated packets are successfully received at the destinations, with all cases where either an increase in range and/or an increase in rate is considered due to diversity. When the channel becomes unreliable due to Rayleigh fading the end-to-end throughput with the high-rates drop; this is because the routes are not stable and are vulnerable to failure more often. The routing algorithm uses the minimum-hop route to the destination that is discovered. This route consists of low-SNR links from the perspective of the high-rate schemes, and with instantaneous fades these links fail to deliver the data packets. Figure 5 shows the standard deviation of hop count; the value is higher for higher data rates; this suggests that route failures are likely happen often with these schemes. Thus, schemes that use diversity to achieve an increase in range overperform the schemes with increased rates.



**Figure 4: End-to-End Throughput at Various Levels of Increase in Rate/Range with Diversity Gain**



**Figure 5: End-to-End Delay for Varying Increase in Rate/Range with Diversity Gain**



**Figure 6: Average Standard Deviation in the Length of Routes with (i) only Path Loss, (ii) With Path Loss and Rayleigh Fading, (iii) With Pathloss, Multipath Fading, Lognormal Shadowing**

Currently we are implementing DSR to perform routing decisions with respect to the link-quality routing metric ETX (from [5]) as opposed to hop count. ETX estimates the number of transmissions needed to send unicast packets between pairs of nodes; thus it considers the communication link quality at the physical layer. Our intuition is, the end-to-end performance when routes choose the higher-reliability links will be different from our observations so far.

## **2. A TDMA based framework approach to the design of a medium access control protocol for MIMO Spatial Multiplexing Communications.**

Spatial multiplexing with MIMO systems allows nodes to simultaneously transmit and/or receive multiple independent streams. This capability obviates the need to “silence” the neighborhoods of the communicating node pair, as was done for the traditional SISO communications. We seek to exploit this capability in a multi-hop network, so that nodes are able to concurrently receive from a multiplicity of transmitters, *provided that* specific conditions for the successful decoding of all received streams are met. By thus enabling spatial multiplexing, network throughput can be increased by a factor linear in the number of antenna elements on the nodes. On the other hand, facilitating this architecture requires a framework that manages the medium access control of individual communications effectively. The choice of the transmitters around a receiver is crucial for successful decoding at the receiver. Our objective is to construct a framework that performs topology control. In a nutshell, the framework divides the links in the network into multiple disjoint subsets. The links share the medium in a time-division approach; at any given time instance only one of the above subsets of links is made active. The membership of each subset is such that communications are enabled with a “bounded” probability of collision.

In the following, we list and define the steps we take towards the design of our framework.

1. We define the characteristics of the individual communications that will be spatially multiplexed; these characteristics define necessary conditions for each packet to be successfully decoded at its receiver in the presence of interference.

In our problem all nodes are equipped with the same number,  $K$ , of antennas. Nodes use their *best* antenna for transmission to the intended destination; the choice is dictated by the feedback of channel state from this destination. Nodes receive a superimposed signal from all transmitters. The post-reception SINRs of individual transmitted streams determine whether they can be correctly decoded.

Received streams are decoded using MMSE-SIC: the symbol with the highest post-reception SINR (signal to interference plus noise ratio) is decoded first, using MMSE. The decoded symbol is then re-modulated and subtracted from the received compound signal. The remaining symbols are iteratively decoded in the same manner; at each step the symbol with the greatest SINR is decoded. This method is called Successive Interference Cancellation using MMSE detection at each step.

We point out that, for all subsequent symbols (after the first), the SINR is degraded if there is remaining un-cancelled interference from previous streams (due to a wrong decision on the corresponding symbol). We assume in our model that, if the signal estimation is in error for some phase of the SIC, none of the subsequent symbols can be decoded at this receiver. Hence, successful detection at each step is mandatory.

2. We associate the physical layer communication model with the network-wide viewpoint of the higher layers, and define our problem globally.

**Problem:** **Facilitate** efficient medium access in an ad hoc network where nodes are equipped with antenna arrays; every node transmits using *one* of its antennas, and receives using *all*.

**Requirements:**

- (i) Each communication (unicast transmission between a particular node pair) must be successfully decoded at its receiver with high probability. In other words, probability of making a decoding error must be extremely small for any receiver.
- (ii) A node must be able to transmit with as little delay as possible; i.e., every transmitter can access the channel frequently.

To summarize, problem asks a partitioning of all possible communications in the network into as few groups as possible, such that the communications in every group are successful with high probability.

3. We show that our problem, i.e. *scheduling* the communications in the ad hoc network while satisfying above requirements, is NP-hard.

**Definition: Set Cover Problem:** Given a universe  $U$  and a family  $S$  of subsets of  $U$ , a *cover* is a subfamily  $C \subseteq S$  of sets whose union is  $U$ .

The *set cover* problem is NP-hard, and can be reduced to our problem. There are approximation algorithms for the set cover problem with known approximation ratios. However, in our problem we also need to construct the family  $S$ . The time needed in order to compute  $S$  is exponential in the number of links in the network. We propose a heuristic-based algorithm for finding  $S$ . In the following, we define the steps of this construction.

4. Roadmap of our proposed solution.

- We generate an “**interference graph**”  $G'=(V',E')$  from the input graph  $G=(V,E)$ ; this is a weighted directional graph having one vertex (e.g.  $u$ ) in  $V'$  for *every directional edge*  $(a,b)$  in  $G$ . Two vertices  $u,v$  are connected by a directional edge  $(u,v) \in E'$ , iff the receiver  $d$  of the

communication link  $v=(c,d)$  detects the transmission from  $a$ , the transmitter of link  $u$ . The weight on the directional edge  $(u,v)$  represents the amount of received power between the transmitter-receiver pair under discussion  $w(u,v)=P_{rcvd}(d,a)$ .

- We use the interference graph in defining **groups** of SISO links that can operate concurrently.

For the signal transmitted over link  $u=(a,b)$  to be decoded, the SINR at the receiver  $b$  should be larger than a threshold  $\gamma$ :

$$\frac{P_{rcvd}(b,a)}{N + \sum_{v \neq u} P_{rcvd}(b, TX(v))} \geq \gamma \quad (2)$$

, where  $TX(v)$  is the transmitter of link  $v$ ;  $v$  is any link such that the receiver of link  $u$  receives  $TX(v)$ 's signals with nonzero power.

Equation (2) above can be rewritten as:

$$\sum_{v \neq u} P_{rcvd}(b, TX(v)) \leq \frac{P_{rcvd}(b,a)}{\gamma} - N \quad (3)$$

The right hand side of Equation (3) quantifies the maximum interference the link  $u=(a,b)$  can accommodate. If the interference exceeds this amount, none of the streams received at receiver  $b$  can be correctly decoded. It is obvious that Equation (3) must be satisfied for every concurrently active link, so that the receivers of each can carry on with successfully reception.

We re-iterate that, SIC decodes the symbol with the highest post-reception SNR at a given instant. Also recall that with SIC, each MMSE iteration must end in correct symbol estimation, in order to have a chance of successful decoding in the subsequent iterations. Thus, in decoding the symbol transmitted over link  $(a,b)$ , in Eqn. (2) above, the summation in the denominator is only carried out over the links  $v$  such that  $P_{rcvd}(j,b) \leq P_{rcvd}(a,b)$  where  $v=(j,k)$ . This because, for all  $v'=(j',k')$  s.t.  $P_{rcvd}(j',b) > P_{rcvd}(a,b)$ , the symbol from  $v'$  has already been (correctly) decoded and its interference on receiver  $b$  has been successfully removed.

- Starting with the maximum-power link<sup>1</sup> in the network and considering one link at a time:

**a.** We compute the maximum interference this link can sustain, based on the above analysis. We denote this value as:

$$ksize(u = (a, b)) = \frac{P_{rcvd}b,a}{\gamma} - N = \frac{w(b,a)}{\gamma} - N. \quad (4)$$

**b.** Every other directional communication ( $v=(c,d)$ ) imposes an interference on the receiver  $b$ , by an amount  $w(u,v)=P_{rcvd}(c,b)$  (Equals the weight of an edge in the directional interference graph). Our goal is to find a set of links  $v'=(c',d')$  such that the sum of  $w(c',b)$  is less than or equal to **ksize(a,b)** in Equation (4). Note that this problem is similar in spirit to the well-known 0-1 Knapsack Problem [4] which is defined as follows:

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<sup>1</sup> The link  $(u,v)$  such that  $P_{rcvd}(u,v)=\max_{(a,b)}(P_{rcvd}(a,b))$ .

Given  $n$  items  $x_1, x_2, \dots, x_n$ , where each item  $x_j$  has a value  $p_j$  and a weight  $w_j$ ; and a maximum weight (capacity)  $C$  that a bag can carry, fill this bag with maximum number of items having maximum value.

Maximize  $\sum_{j=1}^n p_j * x_j$ ,

Subject to  $\sum_{j=1}^n w_j * x_j \leq C$ , where  $x_j \in \{0,1\}$  and  $j=1,2,\dots,n$

- c. The problem of finding the proper set of interferers that the receiver  $b$  of link  $(a,b)$  can accommodate is similar to the 0-1 Knapsack problem with capacity  $k_{size}(a,b)$  and items with weights  $w(d',a)$  which will fill the knapsack.

Currently we are in the process of designing an algorithm, which colors the interference graph using as few colors as possible, and for each color the probability of decoding error at a receiver is arbitrarily small.

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## 6.4 Space-Time Power Scheduling in Large Networks

**PI:** Yingbo Hua

**Student:** Kezhu Hong

**Postdoc:** Bin Zhao and Yue Rong

**Collaborators:** Ananthram Swami and A. Lee Swindlehurst

### SUMMARY OF ACHIEVEMENTS

We have focused on issues of network throughput in the presence of mutual interference in large networks. This focus was motivated by the fact that for large networks the best network spectral efficiency can only be achieved with mutual interference. For example, if the network is scheduled in such a way that no link interferes with another, then the (per link) network spectral efficiency diminishes to zero as the network size increases. But if mutual interference is allowed, the (per link) network spectral efficiency can be lower bounded by a non-zero constant as the

network size increases. Using multi-hop (per link) network throughput as performance measure, we have researched several fundamental issues such as:

- What is the optimal spacing between concurrent co-channel transmissions?
- What is the optimal spectral efficiency of a packet in multi-hop networks?
- How does network topology affect network throughput?
- What is the effect of channel fading on network throughput?
- How can we design distributed link scheduling algorithm optimally?
- How much benefit can we get from the use of multiple antennas in large networks?
- How should multi-user diversity be exploited in multi-hop large networks?
- What is the best way to integrate link scheduling and power control for networks of multiple distributed MIMO links?
- How can we maintain fairness and QoS in networks of multiple MIMO links while minimizing the usage of network resources?

Our research this year has resulted in 2 journal papers published or accepted, 3 journal papers under review and 4 conference papers published. In the following, we highlight a few samples of our technical contributions.

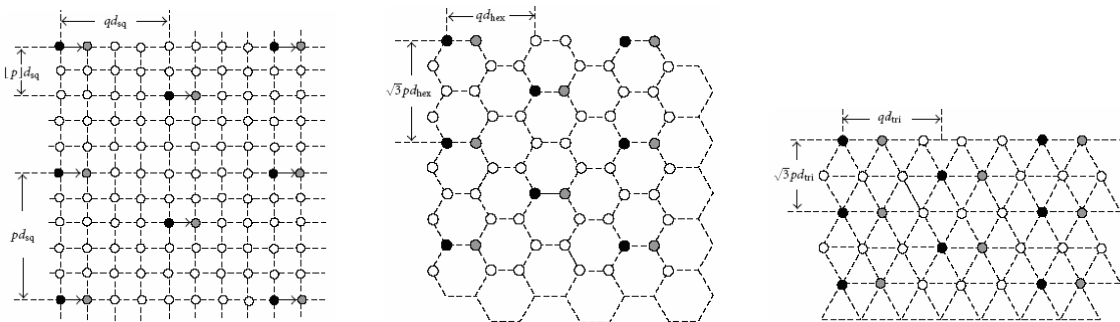
## 1. Maximum Throughput of Large Regular Networks:

To measure the network spectral efficiency of large networks, we use the following two metrics for non-fading and fading cases, respectively:

$$c_{non-fading} = \frac{1}{G} \log_2(1 + SINR) \quad \text{bits-hops/second/Hertz/node}$$

$$c_{fading} = \frac{1}{G} \log_2(1 + \eta) \Pr(SINR \geq \eta) \quad \text{bits-hops/second/Hertz/node}$$

where  $G$  is the (average) number of nodes sharing orthogonally a time/frequency band for each active link in the time/frequency band,  $SINR$  is the signal-to-interference-and-noise ratio for each active link, and  $\log_2(1 + \eta)$  is the spectral efficiency of each packet. For large networks (i.e., the number of nodes is much larger than  $\log_2 P$  where  $P$  is the average power of received signal component),  $c$  is upper-bounded by a constant. The larger the value of  $c$  is, the better is the network spectral efficiency. It turns out that the network spectral efficiency is maximized only when the network is fully loaded (i.e., each node has its own data to transmit to another node).



To investigate the maximum value of  $c$ , we consider a large-scale network of regular topologies (shown above): square, hexagon and triangle, along with the use of the synchronous array method (SAM) for medium access control. The value of  $c$  is optimized over the spacing parameters  $p$  and  $q$ . The following three tables provide the optimal choices of  $p$  and  $q$  for each topology and each combination of  $n$  and  $\epsilon$ . Here,  $n$  is the path loss exponent, and  $\epsilon$  the directivity of directional antennas. The directivity is defined as the ratio of the off-line-of-sight power gain versus the on-line-of-sight power gain.

$c_{\text{SAM,sq}}^*(p, q)^*$	$\epsilon = 1$	$\epsilon = 0.1$	$\epsilon = 0.01$
$n = 3$	0.2166, (2, 3)	1.7914, (1, 2)	2.1668, (1, 2)
$n = 4$	0.4208, (2, 3)	2.3780, (1, 2)	3.0442, (1, 2)
$n = 5$	0.6210, (2, 3)	2.7425, (1, 2)	3.8689, (1, 2)

$c_{\text{SAM,hex}}^*(p, q)^*$	$\epsilon = 1$	$\epsilon = 0.1$	$\epsilon = 0.01$
$n = 3$	0.2794, (1, 3)	2.1297, (1, 1.5)	2.7976, (1, 1.5)
$n = 4$	0.5430, (1, 3)	2.5813, (1, 1.5)	3.8645, (1, 1.5)
$n = 5$	0.8040, (1, 3)	2.7474, (1, 1.5)	4.8132, (1, 1.5)

$c_{\text{SAM,tri}}^*(p, q)^*$	$\epsilon = 1$	$\epsilon = 0.1$	$\epsilon = 0.01$
$n = 3$	0.1863, (1, 3)	1.4198, (1, 1.5)	1.8651, (1, 1.5)
$n = 4$	0.3620, (1, 3)	1.7209, (1, 1.5)	2.5763, (1, 1.5)
$n = 5$	0.5360, (1, 3)	1.8316, (1, 1.5)	3.2088, (1, 1.5)

In order to fairly compare the throughput between different topologies, we apply the following conversion from  $c$  in bits-hops/s/Hz/node to  $\alpha$  in bits-meters/s/Hz/node:

$$\alpha = \frac{D}{N_{\text{hops}}} c \quad \text{bits-meters/s/Hz/node}$$

where  $D$  is a large (multi-hop) distance between source node and destination node and  $N_{\text{hops}}$  is the average number of hops required to travel the distance  $D$ . The following table compares the network throughput in bits-meters/s/Hz/node under the three topologies, non-fading channels and different values of  $n$  and  $\epsilon$ .

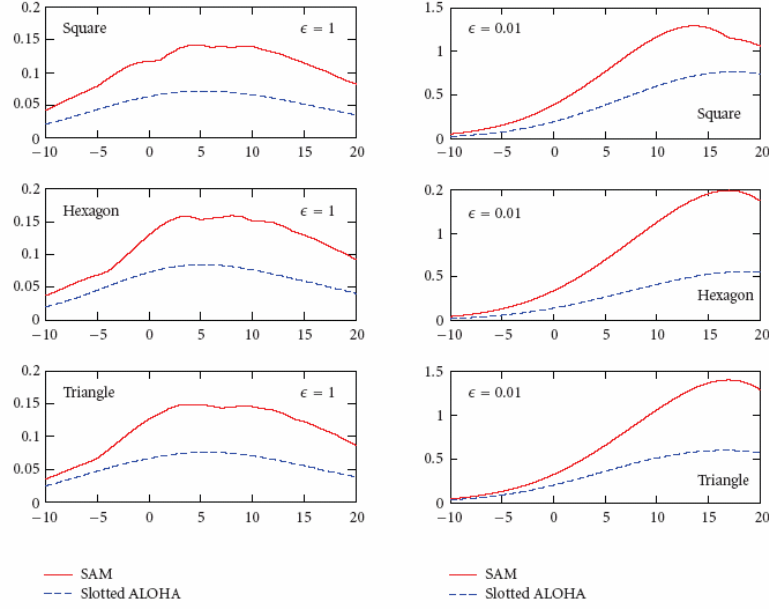
$\alpha_{\text{SAM,sq}}^*, \alpha_{\text{SAM,hex}}^*, \alpha_{\text{SAM,tri}}^*$	$\epsilon = 1$			$\epsilon = 0.1$			$\epsilon = 0.01$		
$n = 3$	0.170	0.193	0.182	1.407	1.468	1.384	1.702	1.928	1.818
$n = 4$	0.331	0.374	0.353	1.868	1.779	1.677	2.391	2.663	2.511
$n = 5$	0.488	0.554	0.522	2.154	1.893	1.785	3.039	3.317	3.127

The above table provides a quantitative range of the best possible network throughput in bits-meters/s/Hz/node that anyone can expect for a large network of single-antenna nodes.

The next set of figures compare the network throughput in bits-meters/s/Hz/node of the SAM scheme and the ALOHA scheme under fading channels (with  $n=4$  and nominal SNR=30dB).



Each figure is  $\alpha$  in bits-meters/s/Hz/node versus  $\eta$  the target SINR value for successful packet reception.



The end-to-end (ETE) delay, also called source-to-destination delay, is of interest as well. In general, the ETE delay can be expressed as

$$T_{ETE} = \lambda \frac{D}{\pi} \sqrt{\rho} T$$

where  $\lambda$  is the ETE delay coefficient,  $D$  is a large ETE distance,  $T$  is the time required for each hop, and  $\rho$  is the node density. The following table compares the ETE delay coefficient for the three topologies:

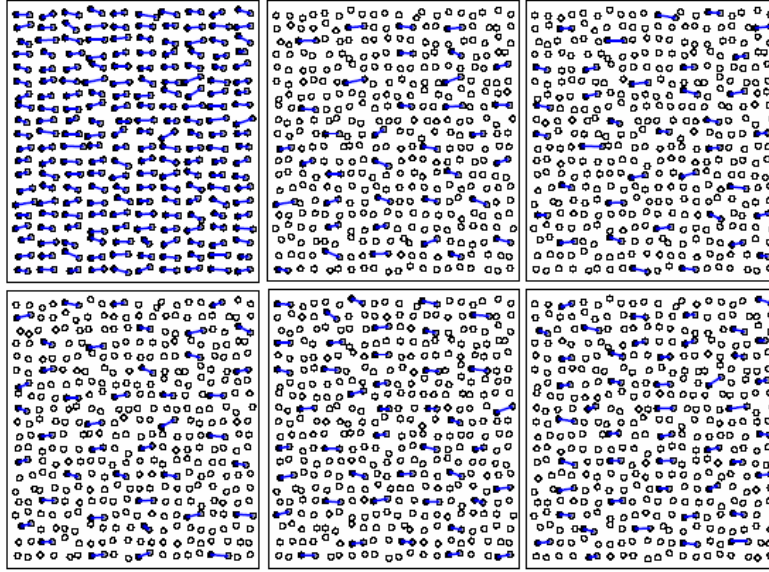
E2E delay	$\epsilon = 1$	$\epsilon = 0.1, 0.01$
$T_{E2E,sq}$	96.00	32.00
$T_{E2E,hex}$	54.71	27.35
$T_{E2E,tri}$	116.05	58.03

We see that the hexagonal topology has the least ETE delay among the three topologies.

## 2. Distributed and Cooperative Link Scheduling of Large Networks:

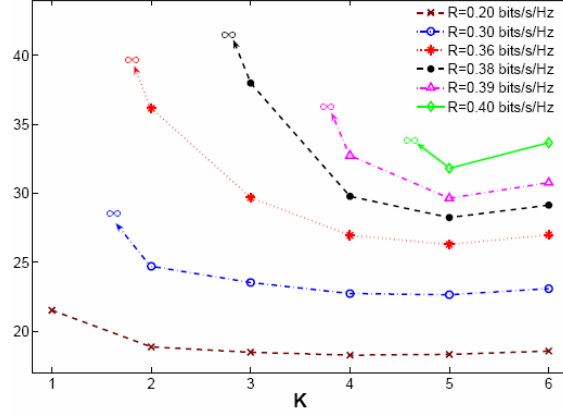
From the previous work, we see that the spacing between concurrent and co-channel transmissions is important for network spectral efficiency. For large networks, the spacing (such as the parameters  $p$  and  $q$ ) can be difficult to determine in a centralized way. To solve this problem, we have developed a distributed and cooperative link-scheduling (DCLS) algorithm. The idea of the DCLS is that all active links cooperatively assign themselves with one or more of

$K$  pre-determined time/frequency bands. The cooperation is done over several iterations synchronized throughout the network. During each iteration, the transmitter of each link (say  $l$ th link) emits a test signal of power  $P_l^{(i)}(1), \dots, P_l^{(i)}(K)$  over the  $K$  time/frequency bands, respectively, and the receiver of each link computes the power of interference over the  $K$  time/frequency bands. Based on the interference power and a modified water-filling algorithm, each receiver computes, and sends back to its transmitter, a new set of allocations of transmission power,  $P_l^{(i+1)}(1), \dots, P_l^{(i+1)}(K)$ . The above iteration repeats for  $I$  times (where  $I$  is pre-determined). At the end of the last iteration, each of  $P_l^{(I)}(1), \dots, P_l^{(I)}(K)$  is applied to a threshold to form a zero/one (i.e., off/on) binary sequence. This sequence governs the assignment of each link to one or more of the  $K$  pre-determined time/frequency bands. The following figure illustrates the performance of the DCLS algorithm.



In the upper left is the original network of 200 active links, each of which requests one or more of  $K=5$  available time/frequency bands. After several iterations of the DCLS algorithm, five subnets are formed, each of which occupies a single time/frequency band. We see that for each subnet the spacing between concurrent co-channel links is quite desirable.

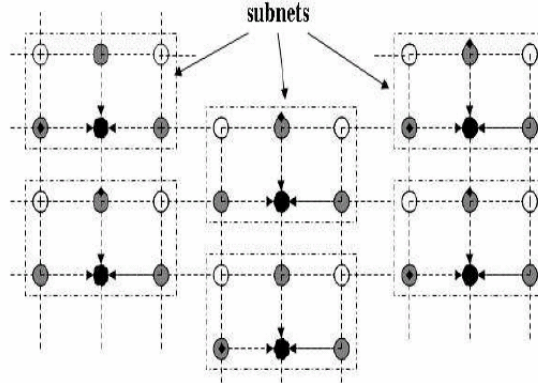
The benefit from the DCLS algorithm can be translated into power saving if a distributed and cooperative power control (DCPC) algorithm is applied to each of the  $K$  subnets. The DCPC algorithm is based on a convex optimization problem, which has a fast convergence. In the following figure, we illustrate the effect of  $K$  on power consumption of the entire network (through the combined use of DCLS and DCPC).



For example, we see that at the network throughput 0.38 bits-hops/s/Hz/node the power consumption of the network is virtually infinite when  $K=1$  or  $2$ . But with a larger  $K$ , the DCLS algorithm reduces the power consumption significantly.

### 3. Impact of Antenna Arrays on Throughput of Large Networks

We have considered a large network of square topology with the following subnet partitions, where node has multiple antennas:

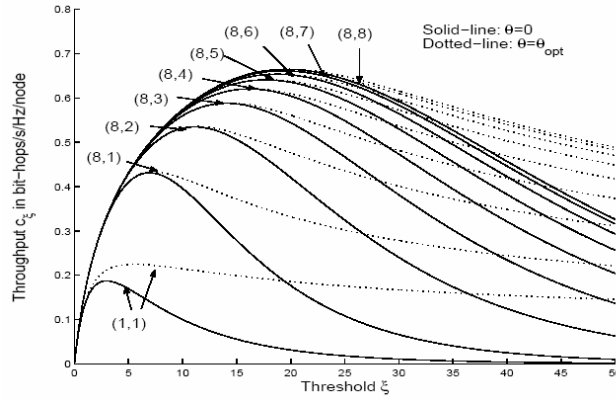


Here, the black nodes are the receiving nodes in a given time/frequency band  $B$ , the gray nodes are the potential transmitting nodes in  $B$ , and the white nodes are idle in  $B$ . In this figure, we have  $n=3$  potential transmitting nodes in  $B$ , and the vertical and horizontal spacing between receiving nodes are  $p=2$  and  $q=3$ , respectively.

We use an opportunistic synchronous array method (O-SAM) for medium access and assume that channel fading is Rayleigh distributed. We let each node carry  $n_r$  receiving antennas and  $n_t$  transmitting antennas. There are three special cases (or schemes) of the O-SAM: 1) receive

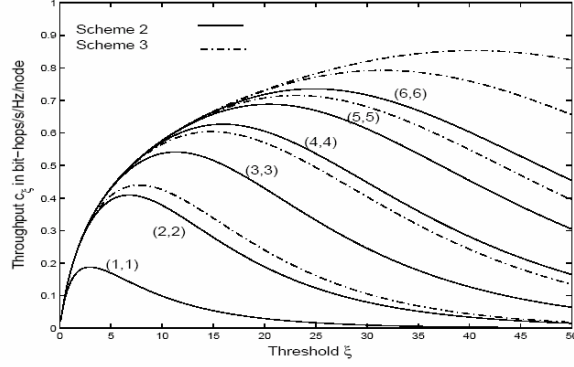
antenna selection, 2) transmit antenna selection, and 3) eigenbeam selection. In case 1, we have  $n_t = 1$  and  $n_r > 1$ , but only a subset of  $n_r^*$  receive antennas having the strongest gains is selected. In case 2, we have  $n_t > 1$  and  $n_r > 1$ , but only the transmitting antenna having the best channel vector (i.e., the maximum norm) is selected. In case 3, we have  $n_t > 1$  and  $n_r > 1$ , but only the best eigenbeam is selected. In addition to the antenna/eigenbeam selection mentioned above, the O-SAM also selects the transmitting node opportunistically. Furthermore, if the best selection in a subnet does not meet a threshold  $\theta$ , the transmission in the subnet is aborted so that the interference to other subnets is reduced.

The following figure illustrates the network throughput in bits-hops/s/Hz/node of O-SAM with receive antenna selection (case 1).



Here, the pair of numbers in parenthesis are  $(n_r, n_r^*)$ , i.e., using  $n_r^*$  receive antennas out of total  $n_r$  receive antennas. The horizontal axis  $\xi_\zeta$  (denoted as  $\eta$  previously) is the target SINR for successful packet reception.

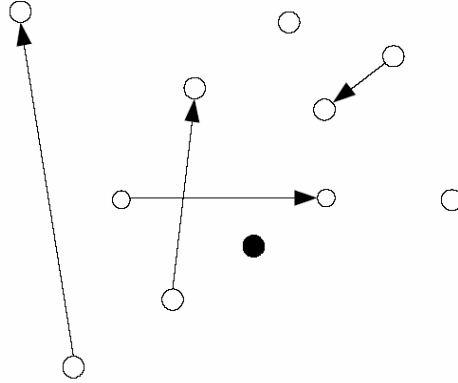
The next figure shows the network throughput in bits-hops/s/Hz/node of O-SAM with transmit antenna selection (case 2) and eigenbeam selection (case 3).



The above two figures provide a quantitative measure of how much network-wide throughput that one can expect out of multiple antennas on each node in a large network.

#### 4. Fairness and QoS based Space-Time Power Scheduling of MIMO Links

An example of ad hoc network with a central scheduler is illustrated below:

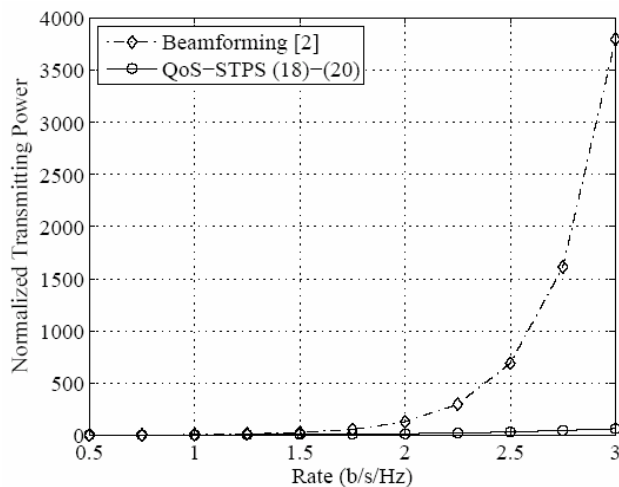


The above figure actually illustrates the active links in a given time/frequency band  $B$ . The black node denotes a central scheduler in  $B$ . The central scheduler can be adaptively selected in tactical situations. There are two approaches to this scheduling problem. One is to maximize a proportional fair utility function, which provides a fair distribution of link throughput and also ensures a high total network throughput. The second is to minimize the total power consumption subject to a desired data rate (i.e., QoS) for each link.

We have considered both slow fading channels and fast fading channels. Because both space and time (as well as frequency) are exploited in our method, the feasible region of link data rates is bounded only if the power is bounded. This is in contrast to many existing space-only power control methods that have a finite feasible region of link data rates even if the power is

unbounded. With the advantage of our method, we can handle the required computation efficiently by using projected gradient.

The following figure compares the power consumption of our space-time scheme with a space-only scheme recently published in the literature:



Here the horizontal axis is the ("original", instead of "composite") data rate in bits/s/Hz from each node in a 5-nodes linear relay network accessing to a common access point. We see that the difference of power consumption between the space-time scheme and the space-only scheme is remarkable.

#### Future plan:

Our future plan includes

- Effect of channel estimation errors on throughput of large networks
- Fundamental understanding of multiple packet reception in large networks
- Throughput analysis of large networks under partial loading (as opposed to full loading)
- Security analysis of MIMO links

## 6.5 Cross-Layer Design and Analysis of MAC and Routing Protocols for Ad Hoc Networks with Multiple Antennas

PI: Prof. Michele Zorzi

### Introduction

During the past year, Dr. Zorzi's research efforts have dealt with a variety of issues at the PHY, MAC and routing protocol layers. In particular, three main areas have been studied:

- 1) The integrated Multiuser detection/MAC protocol developed in the early stages of the MURI project has been further explored and its behavior characterized in more depth. In particular, a detailed approximation of the physical layer Multiuser detection has been developed in order to perform faster but still accurate network simulations. In addition, this protocol has been extended to the multihop case, and new routing issues for multiuser detection MIMO MANETs have been found and explored, with special focus on the implications of MAC choices on routing performance.
- 2) The issues due to directionality in multi antenna MANETs have been addressed, with special emphasis on the problem of deafness. The result of this effort is a MAC protocol specifically designed to overcome the problems of deafness when directional communications are possible. The features of real-world signal processing algorithms have been considered so as to design a protocol that mirrors the actual limitations and advantages of antenna arrays
- 3) The growing importance of Hybrid ARQ in wireless networks has led part of our research into the design of a distributed and effective error control system for MIMO MANETs. As this distributed protocol makes use of collaboration among nodes, this investigation has dealt with the emerging field of cooperation. Finally, the interaction of this error control system with the routing layer as well as its effects on routing protocol design criteria have been considered, and some new issues and strategies for MIMO MANET routing have been uncovered.

In this document, we provide an overview of the main technical issues and contributions, as well as some sample performance results, in these three areas, referring to the specific papers for a detailed description and for an extensive set of results.

## **MIMO MANETs with Decision-Feedback Multiuser Detection**

In the first two years of the project, we have developed a cross-layer PHY/MAC protocol for MIMO ad hoc networks and characterized its performance in typical scenarios. In this third year, we have worked on some refinements of such protocol, on the development of accurate PHY approximations for networking simulation speed-up, and on understanding the interaction of such PHY/MAC techniques with the routing layer.

### *1) Physical level approximation*

From the point of view of physical level (PHY) characterization, Dr. Zorzi's main activity for this year has been to formally summarize and unify the results obtained in the first two years. A journal paper containing all the analytical details of the physical level studies has been accepted for publication in the *IEEE Transactions on Wireless Communications* [J1]. The second year's main effort was to devise a correct strategy to approximate the PHY performance, so as to speed up network-level evaluations. The latter, in fact, need to be performed by taking into account the underlying PHY correctly and thoroughly (to ensure the significance of results) but on the other hand need to be run on a larger time scale than needed for PHY evaluations, making a detailed bit-by-bit simulation of the PHY behavior very time-consuming and often too heavy to be useful in network simulation.

More specifically, consider the MIMO multiuser detection system already introduced last year and described in detail in [J1]. This system assumes that each user has  $N_A$  antennas that can be employed for transmitting or receiving using spatial multiplexing (SM). Namely, a transmitter can send multiple data bits in parallel from different antennas, and the receiver separates the superimposed streams by estimating the channel responses from every transmit to every receive antenna, and then applying a space-decorrelating algorithm [J2]. This algorithm can also be extended to operate in the code domain, allowing the decorrelation of spatially multiplexed CDMA waveforms. In general, it can be assumed that a receiving node is listening to  $K$  transmitters  $\ell = 1, 2, \dots, K$ , each using  $u_\ell$  antennas, for a total of  $U = \sum_\ell u_\ell$  received symbols.

Let  $\mathbf{b} = [b_1 \cdots b_U]^T$  the vector of all symbols received from all antennas in a certain time instant.

Each bit is applied a  $N$ -chip spreading sequence. Let  $\mathbf{S} = [\mathbf{S}_1 \cdots \mathbf{S}_U]$  be the  $N \times U$  matrix containing all  $1 \times N$  column chip vectors, where each chip is normalized to the value  $\pm 1 / \sqrt{N}$ .

Assume also that the channel response is the product of a distance-dependent path loss component,  $\alpha d^{-\beta}$ , and a flat Rayleigh fading gain, modeled as a circularly Gaussian zero-mean, unit-variance complex random variable. The channel responses are organized into a matrix

$\mathbf{H} = (h_{ij})$ , where each element  $h_{ij}$  represents the complex channel gain from the  $j$ th transmit to the  $i$ th receive antenna. The signal received at the  $p$ th antenna can then be defined as

$\mathbf{r}_p = \mathbf{S} \mathbf{C}_p \mathbf{b} + \mathbf{n}$ , where  $\mathbf{C}_p = \text{diag}[\mathbf{H}^{(p, \cdot)}]$  is the matrix whose diagonal elements are the entries of the  $p$ th row of  $\mathbf{H}$ . The application of space-code matched filtering is possible by estimating the channel coefficients  $h_{ij}$ , i.e., path loss and fading gain. Now, this process may be infeasible to perform on a large number of incoming symbols, or simply the receiver may decide to leave out some of the lowest power interfering transmissions in order to save computational power and time. This gives rise to a pure interference contribution that cannot be decoupled by the wanted data streams,  $\mathbf{S}_{\text{int}} \mathbf{C}_{\text{int}_p} \mathbf{b}_{\text{int}}$ . When applying the space-code matched filter on a per-antenna basis, the detection input statistics for the signal becomes

$$\mathbf{Y} = \sum_{p=1}^{N_A} \mathbf{C}_p^H \mathbf{S}^T (\mathbf{r}_p + \mathbf{S}_{\text{int}} \mathbf{C}_{\text{int}_p} \mathbf{b}_{\text{int}}) = \mathbf{R} \mathbf{b} + \mathbf{n} + \mathbf{R}_{\text{int}} \mathbf{b}_{\text{int}},$$

where  $\mathbf{R} = \sum_{p=1}^{N_A} \mathbf{C}_p^H \mathbf{S}^T \mathbf{S} \mathbf{C}_p$  is the correlation matrix for the wanted signals, whereas

$\mathbf{R}_{\text{int}} = \sum_{p=1}^{N_A} \mathbf{C}_p^H \mathbf{S}^T \mathbf{S}_{\text{int}} \mathbf{C}_{\text{int}_p}$  is the result of the space-code matched filtering of interfering signals (those for which the channel response has not been estimated).

The detection takes place by first ordering the received (wanted) signals in order of decreasing receive Signal-to-Noise-Ratio (SNR), and then proceeding in steps. At each step,  $\mathbf{Y}$  is weighed to yield a sample and perform the decision, and finally the detected contribution is removed from the originally received signal. Assuming the use of a linear Zero Forcing (ZF) detector, the weighing vector to apply to  $\mathbf{Y}$  is derived by taking the  $i$ th column of  $\mathbf{R}^+$ , the Moore-Penrose pseudo-inverse of  $\mathbf{R}$ , where  $i$  is the current decoding step.<sup>2</sup> The Bit Error Rate (BER) performance of this process can be approximated by taking an equivalent SNR as follows [J1]

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<sup>2</sup> We will suppose here that real signal constellations are used and assume  $\mathbf{R}$ , and hence  $\mathbf{w}(i)$ , to be real.



$$\gamma(k_i) = \frac{|\mathbf{w}(i)^T \mathbf{R}^{(:,k_i)}|^2 \sigma_s^2(k_i)}{\frac{N_0}{2} |\mathbf{w}(i)^T \mathbf{H}^H|^2 + \sigma_{\text{int}}^2 + \sum_{k \in K(i)} |\mathbf{w}(i)^T \mathbf{R}^{(:,k)}|^2 \sigma_e^2(k) + \sum_{k \in N \setminus K(i+1)} |\mathbf{w}(i)^T \mathbf{R}^{(:,k)}|^2 \sigma_s^2(k)}$$

where in the denominator, the purely interfering signals (second term), the errors made in the detection process and that lead to wrong cancellations (third term) and the signals left to cancel before the completion of the process (fourth term) are all approximated as Gaussian contributions. While this approximation is very tight when the number of incoming streams is less than twice the number of antennas (*i.e.*, the number of complex degrees of freedom available) it may be slightly less precise if the number of incoming signals to decouple is too high (see Figure 7). However, as shown in the following, the network performance prediction capabilities of this approximation are satisfactory. While the interested reader is referred to [J1], [C1] for a more detailed discussion on this topic, a sample of the approximation accuracy in predicting the BER of the system is depicted in Figure 7 (the notation  $(N_T, N_R)$  denotes the use of  $N_T$  transmit and  $N_R$  receive antennas, and only a single transmitter receiver pair is taken into account there).

A second approximation has also been developed that, starting from the tree of all possible mistaken/correct symbol detection combinations, computes reduced-complexity versions of it, by pruning branches that correspond to more than a certain number of detection error events,  $K$ . Sample results are given in Figure 8. Even though the precision of this approximation is as good as that of the Gaussian approximation, the behavior in predicting network performance turns out to be somewhat less accurate (the interested reader is referred to [C2]).

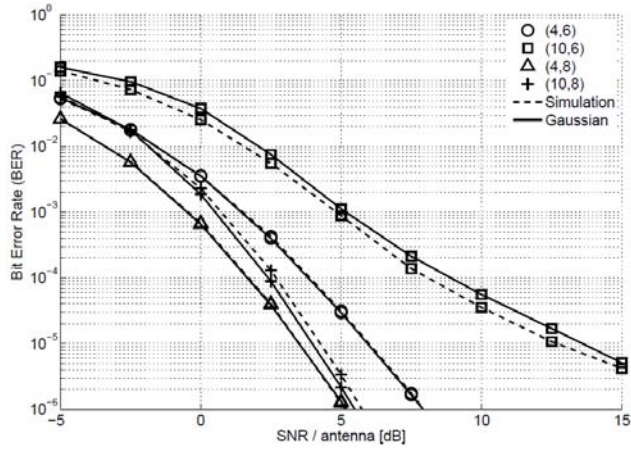


Figure 7. BER for simulation and Gaussian approx.

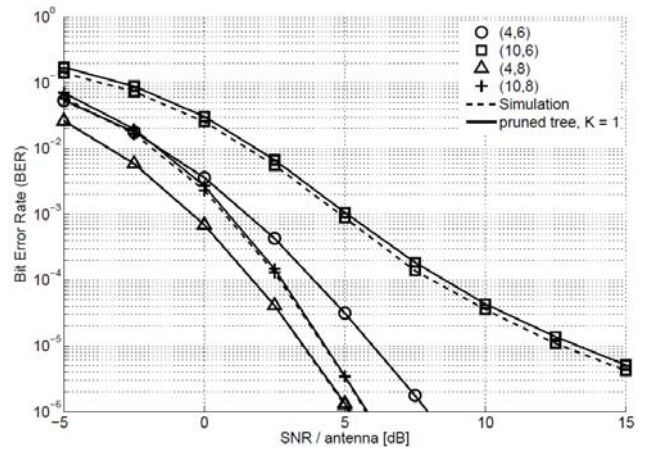


Figure 8. BER for simulation and tree approx.

## 2) Integrated Multiuser detection / MAC protocol / routing

Dr. Zorzi's main line of efforts has been directed toward integrating PHY, MAC and, ultimately, routing design. Designing a MAC layer helps understand the interaction between network

protocols and PHY, giving insight on how the spatial de-multiplexing algorithm should be “driven” in order to achieve transmission effectiveness. The main problem to face here is to answer the following questions: how should the nodes decide what to transmit and to which receiver? How much should transmission parallelism be encouraged? What is the impact of the underlying policies and protocols on routing? The studies carried out during the second year led to the design of a MAC protocol that tries to address these problems. This year, this protocol has been the subject of further investigations aimed at assessing its actual capabilities and at substantiating the assumptions behind it. This has led to a journal paper that has been submitted to the *IEEE Transactions on Wireless Communications* and is currently being reviewed for publication.

In order to summarize what is needed to carry on the discussion, recall that the proposed MAC works in frames. Each frame is composed of 4 slots, that are used to transmit a Request-To-Send (RTS), Clear-To-Send (CTS), data and ACKnowledgment packets, respectively. To form requests for transmissions, nodes account for the underlying PHY capabilities, that translate in the maximum number of antennas that is allowed toward a certain neighbor. This number of antennas constitutes the *class* of the neighbor. Upon receiving RTSs (that are superimposed and thus need to be separated using the multiuser detection algorithm), the addressed nodes apply a policy for granting transmissions. The study carried out has shown that a good solution is to balance between the number of packets that actually reach the receivers and the protection offered through interference detection and cancellation. This policy has been dubbed Follow Traffic (FT). After CTS reception, data transmissions follow, using as many antennas as indicated in the CTS, and sending one Packet Data Unit (PDU), of fixed length, through each antenna. Finally, ACKs are sent back by receivers to provide feedback. If a transmitter sends an RTS but does not receive a CTS, it backs off for a random amount of time, chosen within an exponentially-increasing window. Two backoff policies were considered, Dest-Lock (that blocks attempts toward the node that denied the transmission) and Node-Lock (that blocks transmissions toward all nodes). Note that the nodes need not be strictly symbol-synchronous here. It is necessary to be only frame-synchronous, since the actual performance decrease that would be experienced without symbol synchronization can be obviated by oversampling the receive antenna inputs and running the de-multiplexing algorithm on a larger set of samples. This turns the synchronization problem in a receiver complexity problem.

MAC layer studies have been extended to routing in MIMO ad hoc networks. Multiple solutions have been explored in order to integrate with a routing protocol the cross-layer MAC and PHY algorithms used and developed until now. Following is a summary of the main considerations and results obtained so far, as well as of the most promising future directions.

The first choice was to study an integrated routing and MAC solution together with the multiuser detection at PHY, instead of simply putting a known routing protocol on top of the MAC layer. As most routing protocols require to measure (and/or to keep track of) the “quality” of a link, we extended the concept of “class” to be varied in time and not only based on the distance between the parties, as was the case in MAC evaluations. For example, as traffic varies, nodes may become unable to support the nominal bit rate represented by their present class, resulting in increased transmission errors. For this and similar arguments, it is reasonable to let the class of a node (hence, the “quality” of the node from a communication point of view) both change in time

and depend on a whole set of parameters. For simplicity, it is assumed in the following that the class of a node still reflects the maximum number of antennas affordable, and will restrict it to be either 2, 4, 6, or 8. Using the success ratio as the measure of the reliability of a link (in the form of the ratio between the number of ACKs received and the number of PDUs sent), the following link class updating algorithm has been considered:

$$r_{new} = \alpha \frac{N_{ACK}}{N_{SENT}} + (1 - \alpha) r_{old} ,$$

where  $r_{old}$  and  $r_{new}$  are the old and new reliability measures, respectively, and  $\alpha$  is a weight used to tune the reaction speed of the algorithm to link reliability changes. The new reliability is then compared with an *increasing* and a *decreasing* threshold. If either is exceeded, the class of the link is respectively increased or decreased, though always allowed to have values in the set  $\{2, 4, 6, 8\}$ . Every time the class is changed, the link reliability variable is reinitialized.

This class updating policy (CLupd, blue diamonds), has been simulated and compared to a policy that fixes the class of any link to 8 (CL8, red stars), and the fixed class policy that was initially proposed for MAC evaluations (CLstat, black circles). The results of this comparison can be seen in Figure 9. There,  $N'$  represents the number of interfering users. This figure shows that there is indeed an advantage to be gained in updating the class of a node dynamically. While CL8 may have similar throughput performance to CLupd, yet it proves to yield a lower success ratio.

From the point of view of routing, adapting the class has an important impact. It allows not to overload the de-multiplexing algorithm, because it adapts to neighboring traffic conditions. More importantly, it will limit denials by congested nodes to neighbors requiring to forward multihop traffic, thus helping routed packets to get through.

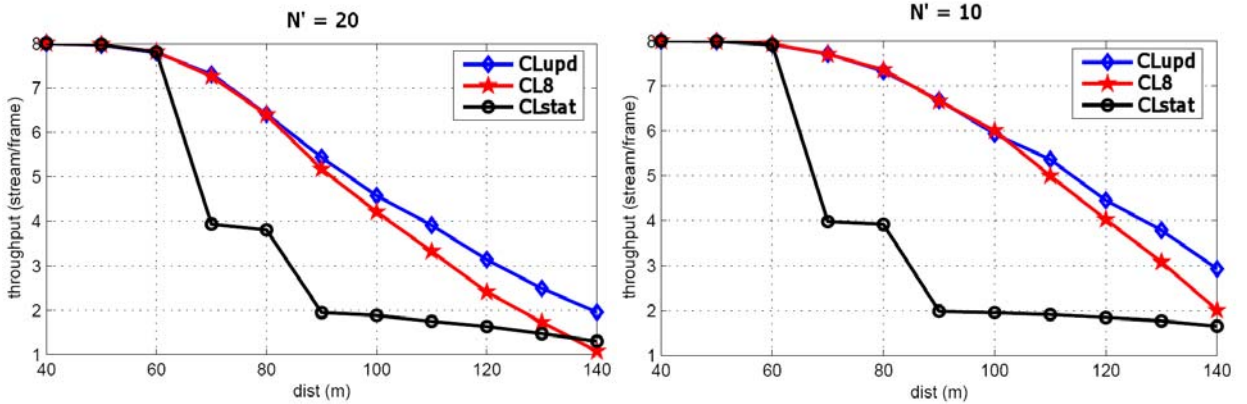


Figure 9. Dynamic class update vs. static class, throughput performance.

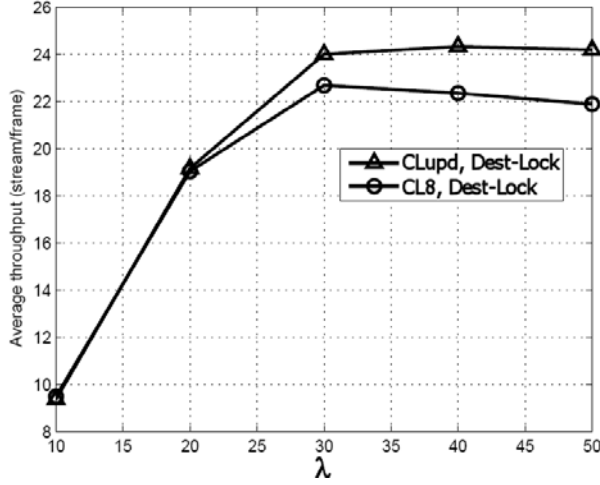


Figure 10. Local throughput CLupd vs. CL8, static routing.

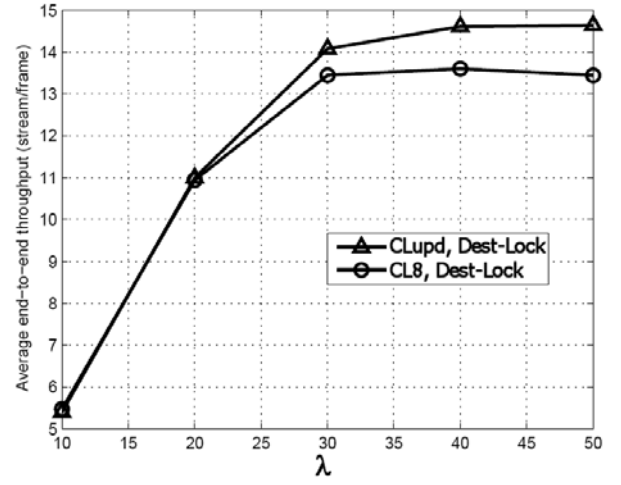


Figure 11. End-to-end throughput, CLupd vs. CL8, static routing.

This approach has also been simulated on a multihop scenario, where each node drives packet toward their destination using fixed shortest path routes. In the experiments presented hereafter, the local (*i.e.*, one-hop) and the end-to-end throughput achieved with the CL8 and CLupd policies have been measured. Figures 10 and 11 show that both the local and the end-to-end throughput benefit from a class updating policy, mainly because CLupd can effectively reduce the number of denied CTs and balance the higher traffic allowed with a more careful distribution over the links.

There is also a tight bond between the routing technique used and the end-to-end throughput performance. For example, the links that constitute shortest-path routes must have a longer reach, hence the signals over these links bear a low average power. Due to the specific details of FT [J3], these links might undergo excessive transmission denials, limiting multihop traffic considerably. If the backoff policy is particularly conservative in limiting transmissions, the difficulties in forwarding multihop packets may be exacerbated. In our experiments, we specifically compared Node-Lock and Dest-Lock. Our preliminary results indicate that even if Node-Lock works very well from the point of view of MAC [C3], [C4], it fails to deliver a sufficient multi-hop throughput, because it forces nodes to stay silent too much. On the other hand, Dest-Lock, that is slightly more aggressive, yields a better overall performance by allowing more transmissions to take place despite denied CTs. Furthermore, updating the class of a neighbor dynamically helps both Node-Lock and Dest-Lock to sustain more throughput.

Exploring different ways to route packets is also of primary importance, as the interaction between shortest-path routing and the FT policy is not optimal. For this reason, we are investigating the feasibility of a dynamic choice of the next hop, that should be performed by taking into account the distance of the node, the link reliability (as measured by the updating policy CLupd), the queue level and the backoff timer of the node. Our results for this case indicate that this yields some throughput advantages, also increasing the number of relaying requests granted by the FT policy. This allows a bigger share of the overall end-to-end throughput to each node, as now they have the chance to select a different relay in case the previously chosen one gets congested. Secondly, we have evidence that using static routing tends

to shrink the network, in that the average number of hops that a packet can travel is shorter. The main reason lies precisely in the worse routing capabilities provided by a fixed choice of the next relay.

The routing results obtained so far are promising and have already highlighted the main characteristic of this study, *i.e.*, to achieve deeper insight into the interactions between PHY, MAC and routing in a MIMO ad hoc network. The studies performed this year have posed a solid base for more routing evaluations. Future directions for this work include finding better metrics for packet forwarding and relay choice, as well as modifying the MAC-routing interaction to control the impact of MAC policies of routing algorithms.

### Cooperative MAC for ad hoc networks with directional antennas

Antenna arrays make possible directional, rather than omnidirectional, transmissions. This leads to significant interference suppression at the physical layer and therefore spatial reuse. In turn spatial reuse may enable concurrent transmissions for neighboring nodes. However, directionality can be detrimental for the MAC layer if proper care is not taken, with deafness as one of the main problems that stem from directionality. Deafness is defined as the lack of response to a Request To Send (RTS), and directionality is a cause of this problem. For example let us consider Fig. 12: node A has been engaged in a communication with D, and a data communication between B and C has started in the meantime. A is not aware of the communication between B and C, because it had been transmitting with D. Node A may try to contact node B, but it would surely fail because B is engaged in another packet delivery. The

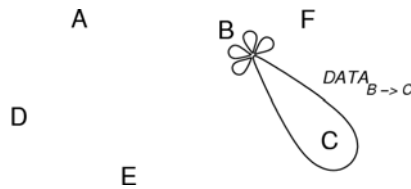


Figure 12: example topology where deafness occurs

situation is even worse, since A would start a backoff procedure that would lead to other RTS transmissions for B, and these are likely to fail too. In the worst case, the Long/Short Retry Limit may be reached and a Link Failure declared. This problem may arise every time a node does not have an accurate perception of the state (*i.e.*, busy/idle) of its neighbors. The use of directional transmissions/receptions exacerbates the issue by trying to exploit spatial reuse while not spreading information on the ongoing communications through the network, as can be seen in the existing literature on directional MAC protocols (e.g., see [C8, C9]).

Therefore, our goal has been the design of some strategies that may reduce the extent of this problem and prevent its effects. Deafness is caused by the missed reception of control packets (especially RTS/CTS) that hamper the virtual carrier sense mechanism. Our basic guideline has been the concept of *deafness prevention*, which means to keep track of all the communications in the neighborhood in a Communication Register (CR). This prevents a node from contacting a busy neighbor. Deafness prevention hinges on three elements:

**Circular Handshaking:** this concept has been introduced by Jakllari et al. in [C10]. It is a system for delivering control packets (RTS/CTS) omnidirectionally but with the extended range provided by antenna array. It is implemented by transmitting the packet using beamforming in different directions until the whole horizon is swept. This approach may

inform more nodes about an incoming communication and thus prevent some nodes from contacting a possibly busy terminal.

**Multiple Receptions:** The receiver of a data packet can normally listen to a single frame (the one sent by the transmitter) by combining the signals from the different antennas that yield the packet by means of a beamforming vector. However, if signal processing power is available, the node can decode multiple packets by using a beamforming matrix, rather than a beamforming vector. Each row of the matrix is tuned towards a specific direction. By this signal processing method, well known in the physical layer community, it is possible to decode multiple packets at the same time and therefore keep listening to control frames sent by other nodes while receiving DATA. This simple method (which, surprisingly, has never been explicitly considered in the design of MAC protocols for directional MANETs) can keep the receiver's CR updated at very little incremental cost.

**Cooperation among Nodes:** This concept is the novel idea that we have proposed.

Whenever a node (say, node A) ends its transmission, its neighbors (including the receiver of the transmitted packet) check their CR to see if they have updated it with information on links that started while A was busy. If this happens, terminals send a coop packet to A. This cooperation packet includes CR updates, that have been collected by idle nodes or the receiver. Several terminals may simultaneously send their packets to the transmitter, but since this node can detect multiple frames at the same time, they are unlikely to collide. This is the key concept that can keep also the transmitter's (and not only the receiver's) CR updated. In order to fully grasp the potential of this technique, an ideal scheme has been considered to provide an upper bound for the performance of a protocol employing cooperation (called B-CMAC). B-CMAC delivers ideal cooperation packets, which are transmitted at zero power (thus they do not cause interference) and perfectly update the addressee's NAV. On the other hand, a real cooperative protocol (called L-CMAC) has been implemented as well. With L-CMAC, packets include information about a single element in the NAV.

These three elements have different capabilities to reduce deafness. The Circular RTS/CTS MAC by Jakllari et al. (CRCM) uses only the Circular Handshaking. We have also developed a fictitious protocol, called MUD, that employs the Circular Handshaking and Multiple Receptions features. Finally, B-CMAC and L-CMAC employ all the features for deafness suppression listed above.

By preventing deafness, a node can avoid to contact neighbors that are unavailable, thus saving time, RTS packets (which cause interference) and energy. Fig. 13 reports the percentage of packets that each protocol addresses to deaf nodes. It is clear that MUD alone can already provide significant gains over CRCM, but B-CMAC can further cut deafness significantly (by about a factor of 4 with respect to CRCM). Moreover, we found that link failures (defined as the event that the handshake fails because the Short Retry Limit is reached) are reduced by a factor of 5 against CRCM. In addition, the significantly reduced number of deafness-related failed handshakes also enables to spare 66% of the energy used by CRCM for the same amount of delivered data (Fig. 14). Finally, Fig. 15 shows that significant throughput improvements are achievable and an optimal usage of cooperation is able to greatly reduce congestion effects. More details and performance comparisons can be found in [C7].

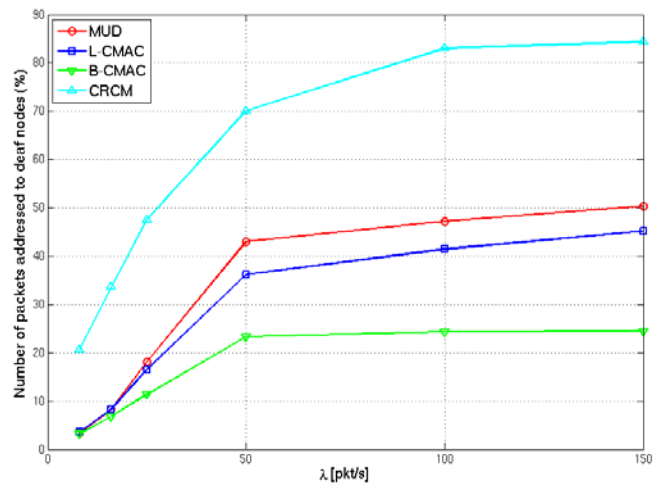


Figure 13: Deafness vs load

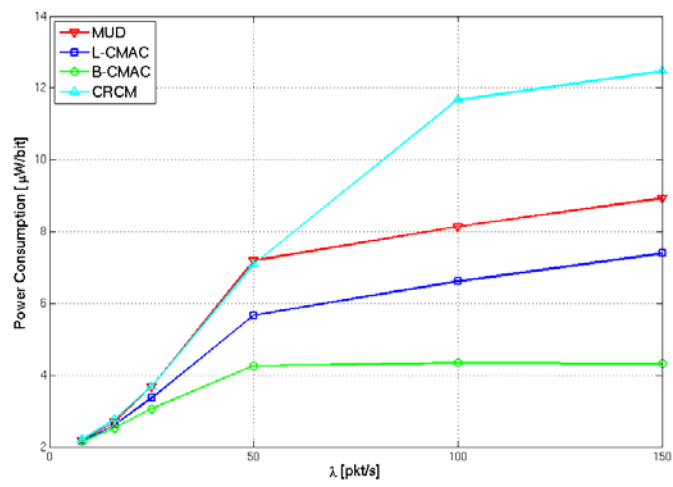


Figure 14: Power Consumption vs load

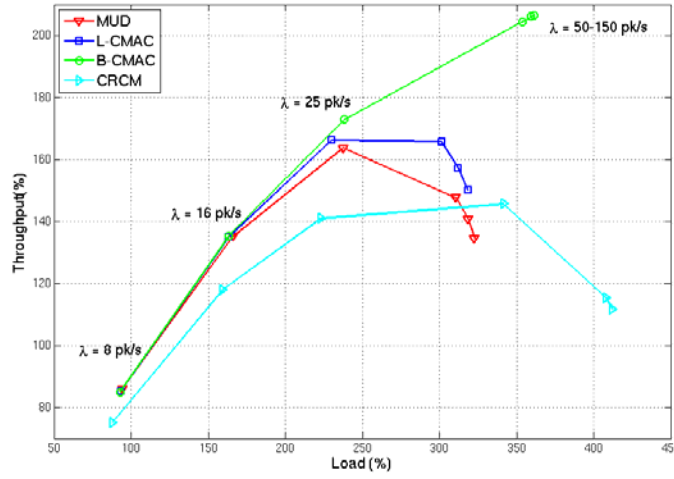


Figure 15: Power Consumption vs load

## Cross-Layer Cooperative MIMO System

In [C5], [J4] we have investigated another communication scheme based on the MIMO BLAST PHY described before, that implements a Hybrid Automatic Retransmission reQuest (HARQ) protocol to deliver packets to their intended destination. As in the previously presented MIMO BLAST protocol, we let nodes in the same area simultaneously access the channel, but in this case we focus on asynchronous access. Thus, due to transmissions starting and ending, the interference power perceived at receivers is highly variable in general. HARQ error control protocols, providing greater adaptability to the channel conditions compared to simple ARQ or FEC protocols, appear to be an effective solution to preserve the network performance. Moreover, we exploit the potential of the MIMO PHY layer to set up a cooperative protocol that realizes a distributed HARQ scheme to improve the network efficiency (note that the cooperative character of the scheme is at the transmission level, and is different from the type of cooperation described in the previous section). The capability of the PHY to support several simultaneous communications allows the efficient deployment of the coordination needed by cooperation. Moreover, in MIMO networks the amount of required coordination is highly reduced by the possibility for the source and cooperating nodes to transmit simultaneously. Thus, the PHY layer has a substantial influence on the proposed protocol design and operations. Results for this MIMO cross-layer cooperative scheme have been obtained through both analysis and simulation. We also present some preliminary results on the integration of the proposed scheme with a cooperative routing protocol.

### 1) PHY and MAC

We consider an ad hoc network where nodes are equipped with an array of  $N$  antennas each. The transmitter and receiver architecture are those described in the physical layer approximation section.

Since traditional CSMA/CA protocols, trying to avoid collisions, do not exploit the potential of the MIMO PHY, we designed a MAC protocol with the aim of increasing communication



parallelism. To establish communications, nodes perform a handshake phase, where short request and confirmation packets are exchanged between the source and its intended destination. Unlike in CSMA/CA, where the RTS/CTS exchange is used to reduce the probability of collision, here the handshake phase is used to probe the destination's availability, and thus to preserve the network efficiency avoiding the transmission of long data packet to unreachable or busy nodes.

## 2) HARQ Protocol

The performance of the decoding algorithm is highly dependent on the received power, the number of incoming signals, and the channel conditions. Since all these may change during a transmission, the estimation of the coding gain needed cannot be performed effectively in the handshake phase. Our HARQ scheme, called Layered Coded System (LCS), first encodes packets with a rate-compatible low-rate code. Each retransmission is divided into phases, in which the source transmits a fragment of the obtained codeword, and the destination sends back a feedback packet in which it reports whether or not it succeeded in decoding the information based on the portion of codeword received so far (including previous phases). Upon a failure a further phase is performed, in which the source and the destination send out a new fragment of the codeword (whose size may depend on what the destination previously received) and a feedback packet, respectively. The process continues until a success is achieved or the maximum number of phases is reached (in which case an independent attempt is rescheduled after a random backoff interval). An example of the proposed transmission scheme is depicted in Fig. 16(a).

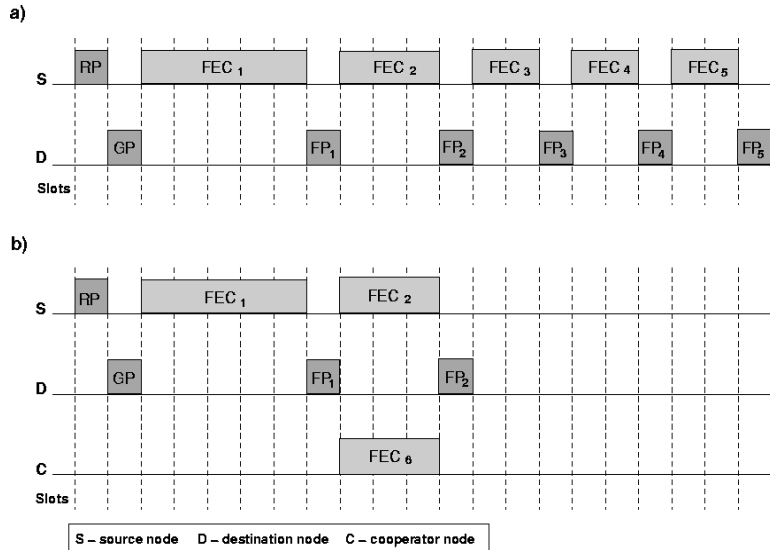


Figure 16: Example of transmission for the non-cooperative (a) and the cooperative (b) protocol.

## 3) Distributed HARQ Protocol

In its distributed version, called Layered Cooperative Coded System (LCCS), our HARQ protocol allows idle nodes that i) have an SNR towards the destination that is not worse than that of the source and ii) decoded the source packet correctly, to also act as sources, re-encoding the packet and transmitting part of the codeword in the following phases. These nodes, called cooperating nodes, transmit in parallel with the source. Thus, at each phase, the destination exploits multiuser detection to possibly receive several fragments of the codeword through

independent channels, thereby increasing the diversity order and the coding gain. The tradeoff is between these two benefits and the interference due to the multiple simultaneous transmissions.

#### *4) Implementation*

The presented scheme admits several possible implementations. As a first case study, we propose an implementation based on Reed Solomon block erasure codes. Packets are divided into a set of  $k$  blocks, that are encoded obtaining a set of  $n$  blocks. Each block is divided into streams, each transmitted with one antenna of the array. The original packet is retrieved if the destination correctly decodes at least  $k$  blocks of the coded set. In each phase, the source and each of the cooperating nodes send exactly the number of blocks that the destination needs in order to be able to decode the packet.

We have considered three cooperation schemes. In all three, only nodes that meet the SNR requirement are considered as possible cooperators (note that the determination of whether or not this condition is met is possible by listening to the handshake packets). In the basic LCCS mechanism, each potential cooperator will decide to cooperate if it is not currently involved as a transmitter or receiver in another data exchange. This takes into account the effect of cross-traffic and node activity on the cooperation mechanism, which is often ignored in similar studies. In addition, we considered two other policies for cooperating node selection: i) idealized LCCS (ILCCS): at most  $K_c$  nodes among the set of nodes that correctly decoded the source packet and match the SNR conditions are chosen. In particular, the  $K_c$  nodes with the highest SNR to the destination are selected; ii) forced LCCS (FLCCS): an idle node that correctly received a handshake and matches the SNR requirements is forced to keep idle state to hear the forthcoming communication and, if it correctly decodes, to cooperate. Note that in this case cooperation has higher priority than the node's own activity.

#### *5) Results*

As a first step we modeled a single link with a Markov process to gain fundamental insights on the proposed system performance. Then, we performed accurate simulations of a complete single-hop network (all nodes are within range of each other) to investigate the impact of the presented cooperative MAC/HARQ protocol on the whole system. As an example, Fig. 17 shows the average overall throughput achieved by the various protocols as a function of the per node arrival rate. It is possible to observe that ILCCS and LCCS outperform the LCS protocol in terms of throughput, whereas FLCCS exhibits the worst performance. While LCCS and ILCCS achieve a good balance between cooperation advantages and generated interference, FLCCS results in an excessive cooperation effort, that overloads receivers and commits resources for communications that achieve success at the first phase and thus do not need cooperation. In Fig. 18 the average failure probability as a function of the network size is depicted. All cooperative protocols guarantee a significantly improved average link reliability with respect to LCS, thanks to the diversity and coding gain provided by the cooperative HARQ, as expected. A more detailed description of the schemes considered, as well as a more comprehensive set of results, can be found in [C5], [J4].

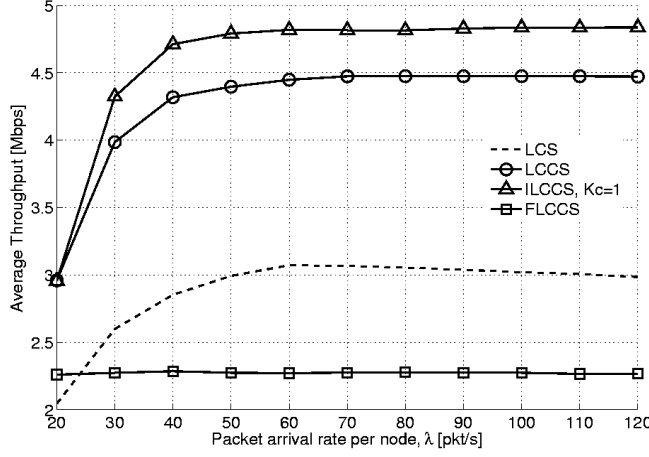


Figure 17: Average throughput as a function of the per node arrival rate.

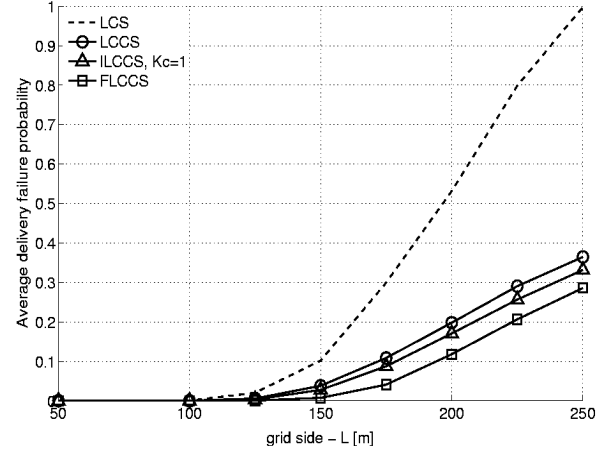


Figure 18: Average delivery failure probability as a function of the network size.

### 6) Cooperative routing

The proposed protocol exploits cooperation only to increase the efficiency of single hop communications. We are in the process of extending our scheme by introducing cooperation at the routing level as well. In our scheme, cooperation is used to dynamically change the path when the channel between the current packet transmitter and the predefined routing relay suffers a fading dip. In particular, while packet delivery to final in-range destinations is solved with a protocol similar to the distributed HARQ scheme described above, we designed a different cooperative policy when the intended receiver is a routing relay. In this case, if the current destination fails to decode the packet, one of the nodes that correctly decoded it and that have a number of hops to the final destination at most equal to the current destination is selected to be the routing relay. Then, the transmitting node releases the packet, and the forwarding to the next hop destination is performed by the selected node. Thus, we try to avoid inefficient transmissions over channels with poor instantaneous conditions, to both increase efficiency and decrease interference in the network. Under bad channel conditions, and when none of the relay candidates is available, the distributed HARQ protocol is activated also when the current destination is not the final destination, to increase the probability of an advancement toward the final destination of the packet.

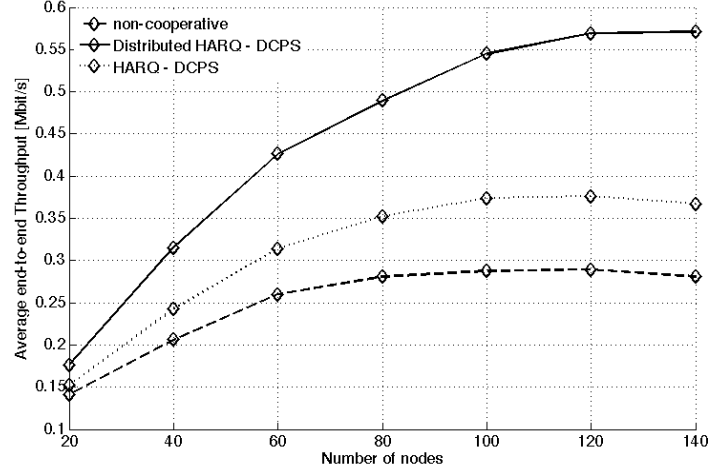


Figure 19: Average end-to-end throughput as a function of the number of nodes.

As an example, Figure 19 shows some preliminary results for the average throughput as a function of the number of nodes in the network. The throughput is averaged over 20 random topologies in a fixed area of 500x500 m. We compare the proposed scheme, that implements dynamic cooperative path selection (DCPS) and distributed HARQ, with the non-cooperative case (fixed routing path and HARQ protocol) and a protocol that provides only dynamic cooperative path selection. It is possible to observe that the use of dynamic path selection improves the performance in terms of end-to-end throughput with respect to the non-cooperative case. This is due to the higher efficiency of the links activated for the packet forwarding, that does not only improves the single packet delivery performance, but also reduces the overall interference level. However, the integration of the distributed HARQ scheme with the dynamic cooperative path selection provides a substantial improvement. Some other initial results show that this protocol achieves the best performance, in terms of throughput, delay, efficiency and failure rate in both one-hop and multi-hop communications [C6].

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## **6.6 Cognitive Radio for Ad-Hoc Networks**

**PI: Larry Milstein**

### **SUMMARY OF RESEARCH RESULTS**

#### **1. Cognitive Radio based Ad Hoc Networks – Qi Qu**

Following our preliminary work in the previous year, we considered the design of a cross-layer multi-user resource allocation framework using a cognitive radio perspective for communications in battlefield ad hoc networks. Our problem is as follows: in an ad hoc network, at a given instant, multiple CR users have data to transmit over the spectrum, but there are already some pre-existing users that occupy the spectrum. In order to avoid interference to existing primary users, each CR user has to detect the availability of each subcarrier, and it can only select subcarriers from its corresponding available subcarrier set. By appropriately selecting the subcarriers, the objective is to minimize the required power consumption while satisfying the BER and data rate requirements of the CR users. The goal is to find the optimal subcarrier assignment for each CR user, as well as the corresponding optimal power and bit allocations.

In this work, we consider a multi-carrier system where the entire spectral range is first sensed, and then those un-used subcarrier bands can be employed by cognitive radio (CR) users, thus increasing the spectral utilization. Because we must avoid noticeable interference to the existing users, we propose a mechanism to detect the availability of a subcarrier by sensing the RF spectrum, and a local node cooperation scheme is also used to improve the detection performance. Given all the necessary information, such as the availability of each subcarrier, the corresponding noise power and the channel gain, in order to utilize the system resources efficiently, a distributed multi-user resource allocation mechanism is proposed due to the lack of central control in ad hoc networks. Since detection errors are unavoidable and multiple CR users may select the same subcarrier to transmit due to the distributed algorithm where each CR user only has its local information available, in order to protect the existing users in the network and facilitate the access process, we also provide an adaptive power control algorithm with user protection and adaptive rate control when the distributed approach is used.

In this work, we have considered the details of the system design for the use of cognitive radio concept in ad hoc networks and examined the performance of a cognitive radio based ad hoc network in face of narrowband interference, primary user existence, and node cooperation. We found that in order to employ cognitive radio in ad hoc networks, a judicious design of an adaptive resource allocation combined with an effective spectrum detection mechanism is necessary to achieve decent system performance.

In particular, our studies show that system performance is greatly affected by environmental conditions, such as the underlying narrowband interference and the existence of primary users. More specifically, as more primary users and more narrowband interference are present, system performance degrades. Since under these conditions, less system resources are left for CR users and more detection errors may occur, thus more conflicts may take place during transmissions. However, due to the proposed node cooperation and the proposed power control algorithm, the

performance degradation due to the existence of primary users and narrowband interference is graceful.

Our results also indicate that in order to achieve satisfactory system performance, node cooperation is necessary to be employed in a cognitive radio based ad hoc network where central control is not available. By doing so, local information, such as the availability of each subcarrier, can be exchanged among users within certain distance, and as a result, better system performance can be achieved.

## **2. Waveform Design - Andrew Ling**

First, we developed a unified approach to deriving closed-form expressions for the probability of error of systems in which the final test statistic is a general Hermitian quadratic form in zero-mean complex Gaussian random variables. This technique can take into account channel estimation errors and is applicable to both independent and correlated Rayleigh fading channels. Problems in which this technique can be applied include maximal ratio combining, Alamouti space-time block coding, and differential detection.

We then extended our previous comparison between multi-carrier direct sequence code division multiple access (MC-DS-CDMA) and multi-carrier code division multiple access (MC-CDMA) by considering a 2x2 multiple-input multiple-output (MIMO) scenario (i.e., two transmit and two receive antennas) in which Alamouti space-time block coding is used to obtain fourth-order spatial diversity. As in the previous comparison, we constrained both systems to use the same data rate, bandwidth, and transmit power. Also, we made the following assumptions regarding the MIMO channel:

- a) Between each transmit-receive antenna pair, we have a slowly-varying Rayleigh fading channel, with independent fading between different transmit-receive antenna pairs.
- b) The coherence bandwidth of each spatial channel is equal to the bandwidth of one MC-DS-CDMA sub-band.
- c) Along each spatial channel, the fading between different MC-DS-CDMA sub-bands is independent. As for the MC-CDMA system, we assume a correlated block fading model (in frequency), where the MC-CDMA sub-bands are divided into blocks. Each block corresponds to one MC-DS-CDMA sub-band, such that there is flat (perfectly correlated) fading across the sub-bands in each block and independent fading between sub-bands of different blocks.

To estimate the channel gains at each frequency, we simply took the sample average of the output test statistics associated with the multiple pilot symbols transmitted at the beginning of each data frame. Finally, using the aforementioned unified approach, we derived closed-form expressions for the probability of error of both systems, and we compared the performances of the two systems for different data rates, number of users, and number of pilot symbols used in each channel estimate to analyze the trade-off between spatial/frequency diversity and channel estimation errors.

Since the combination of multiple antennas and Alamouti space-time block coding already gives fourth-order spatial diversity, and further increases in diversity only yield diminishing gains,

there is more incentive in using the multiple sub-carriers in both systems to increase the data rate. Still, we compared the performances of the two systems for low as well as high data rates. Based on our closed-form expressions for the probability of error, our numerical results showed that for lower data rates, MC-DS-CDMA performed better than MC-CDMA in both the single- and multi-user cases for practical SNR values and number of pilot symbols used in each channel estimate,  $Q_P$ . However, MC-CDMA eventually outperformed MC-DS-CDMA if we increased  $Q_P$  without bound (i.e., when we had perfect channel state information (CSI), since the SNR of the channel estimates approaches infinity). For higher data rates, we obtained trends that were similar to the ones observed in our previous comparison between the two systems, where we considered the single-input single-output (SISO) scenario with only one transmit and one receive antenna. In the single-user case, there existed an SNR value  $x_t$  such that MC-DS-CDMA gave a lower bit error rate for SNR values less than  $x_t$ , while MC-CDMA performed better for SNR values greater than  $x_t$ . This showed that the effects of channel estimation errors dominated at low SNR, while the effects of diversity dominated at high SNR. Also, we observed that MC-CDMA became the preferable system at a lower and lower SNR value as we increased  $Q_P$ . In the multi-user case, MC-DS-CDMA was again the better system at low SNR. At high SNR, however, the effects of diversity were overshadowed by the presence of multiple access interference (MAI), which resulted in an error floor. As a result, for small values of  $Q_P$ , MC-DS-CDMA gave better performance at high SNR as well, but the MC-CDMA system eventually yielded better performance as we increased  $Q_P$ .

### **3. Constrained and Cooperative MIMO Communications in Wireless Ad Hoc Networks – Qi Qu**

In modern wireless communications, enhanced spectral efficiency can be achieved by the use of multiple-input-multiple-output (MIMO) systems. Recently, MIMO has attracted extensive attention and various techniques have been proposed for both cellular systems and ad hoc networks to achieve improved system performance. However, in wireless ad hoc/sensor networks, direct employment of MIMO to each node might not be feasible since, MIMO might require complex transceiver and signal processing modules, which result in high power consumption. Furthermore, nodes in wireless ad hoc networks/sensor networks are often powered by batteries with limited energy. This makes direct application of MIMO to each node inefficient from a power-efficiency point of view. Also, nodes in an ad hoc/sensor network might be of small physical size, which precludes the implementation of multiple antennas at each node.

In order to address this point, we investigate the issue of cooperative node selection in cooperative MIMO communications for wireless ad hoc and sensor networks, where a source node is surrounded by multiple neighbors and all of them are equipped with a single antenna. Given the power, delay and data rate constraints, a source node dynamically chooses its cooperative nodes from its neighbors to form a virtual MIMO system with a destination node which has multiple antennas, as well as adaptively allocates the power level and adjusts the constellation size for each of the selected cooperative nodes. We consider the optimization of all these parameters given some system constraints by judiciously considering both the local information distribution and the long-haul transmission involved with cooperative MIMO technique, and the delay/power consumptions involved in each of the two procedures.



#### 4. Multicode MIMO in Mobile Ad-Hoc Networks – A. Chockalingam

In this work, we investigated a multicode (MC) multiple input multiple output (MIMO) techniques that can be employed to achieve high data rates in mobile ad-hoc networks. It is well known that spatial multiplexing using multiple transmit and receive antennas (V-BLAST) can be used to increase data rates without requiring additional bandwidth. In a mobile ad-hoc network scenario, where communication nodes are mounted on moving platforms (like jeeps, trucks, tanks, etc.), use of V-BLAST requires that the number of receive antennas at a given node must be greater than or equal to the sum of the number of transmit antennas in all its neighbor nodes. This limits the achievable spatial multiplexing gain (data rate) for a given node.

For the above scenario, we proposed to achieve high data rates per node through multi-code direct sequence spread spectrum techniques in conjunction with spatial multiplexing (V-BLAST). In the proposed multicode V-BLAST system, the receiver experiences code domain interference (CDI) in frequency selective fading, in addition to space domain interference (SDI) experienced in conventional V-BLAST systems. Accordingly, we proposed interference cancelling receivers that employ a linear parallel interference cancellation (LPIC) approach to handle the CDI, followed by conventional V-BLAST detector to handle the SDI. RAKE combining at the LPIC output is also proposed to reduce complexity. We analyzed the bit error performance and complexity of the proposed detectors. An example of performance comparison between various detectors is shown in Fig. 20.

The findings of this work were presented in IEEE GLOBECOM'2006, San Francisco, in December 2006. Subsequently, we have extended this work to include asynchronicity among various nodes in the system model. A journal paper is being submitted from this work. We are also working on including the effect of channel estimation errors.

- Improved Linear LPICs

In this work, we propose linear parallel interference cancellation (LPIC) algorithms that have better convergence characteristics compared to other LPICs known in the literature.

Taking the view that a LPIC can be seen as a linear matrix filter, we propose new linear matrix filters that can result in improved bit error performance compared to other LPICs in the literature. The motivation for the proposed filters arises from the possibility of avoiding the generation of certain interference and noise terms in a given stage that would have been present in a conventional LPIC (CLPIC). In the proposed filters, we achieve such avoidance of the generation of interference and noise terms in a given stage by simply making the diagonal elements of a certain matrix in that stage equal to zero. Hence, the proposed filters do not require additional complexity compared to the CLPIC, and they can allow achieving a certain error performance using fewer LPIC stages. An illustration of the better convergence characteristics of the proposed LPICs is shown in Fig. 21.

We also extend the proposed matrix filter solutions to a multicarrier DS-CDMA system, where we consider two types of receivers. In one receiver (referred to as Type-I receiver), LPIC is performed on each subcarrier first, followed by multicarrier combining (MCC). In the other

receiver (called Type-II receiver), MCC is performed first, followed by LPIC. We show that in both Type-I and Type-II receivers, the proposed matrix filters outperform other matrix filters. Also, Type-II receiver performs better than Type-I receiver because of enhanced accuracy of the interference estimates achieved due to frequency diversity offered by MCC.

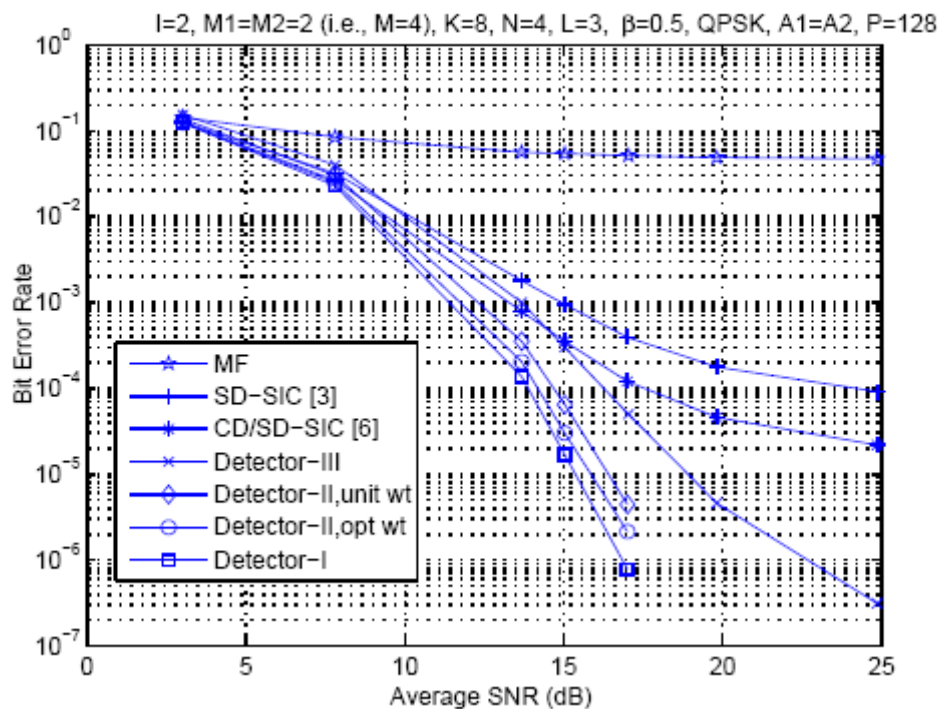


Fig 20: BER performance of the proposed Detectors for multicode V-BLAST.  $I = 2$ ,  $M_1 = M_2 = 2$ ,  $K = 8$ ,  $N = 4$ ,  $L = 3$ ,  $\beta = 0.5$ , QPSK.  $P = 128$ .

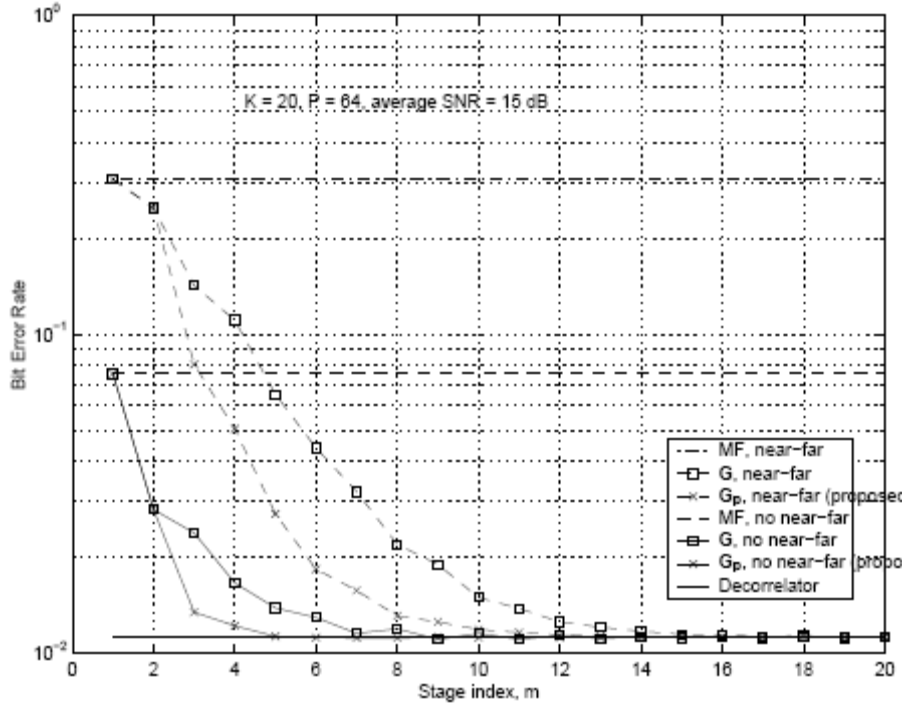


Fig 21: BER performance of various linear matrix filters – i) conventional filter  $G_{(m)}$ , and ii) proposed filter  $G_p(m)$ .  $M = 1$ ,  $K = 20$ ,  $P = 64$ , average SNR = 15 dB. Near-far as well as no near-far conditions.

## 6.7 Information Efficiency and Transmission Range Optimization for FH-CDMA Ad-Hoc Networks

PI: James Zeidler

GSR: Haichang Sui

### Previous work and background

FH-CDMA is a promising PHY waveform for tactical mobile ad hoc networks because of its AJ capability, LPD/LPI, and operability in non-contiguous spectrum. In addition, FH-CDMA is robust to the near-far problem, while DS-CDMA requires either accurate power control or multi-user detection, which may not be practical in the MANET due to the absence of central control or a priori knowledge of interfering users' spreading sequences. For several fading models, performance comparison between FH and DS CDMA systems also favors the former in distributed multiple-access networks. Due to the multiple-access capability from FH-CDMA, design of MAC protocol can also be much simplified and issues like unfairness and throughput degradation in the CSMA/CA protocols may be alleviated, while complexity and overhead involve in spatial-division multiple-access protocols in may be reduced.

We extended previous work on FH-CDMA from single transmit antenna with FSK/DPSK to multiple transmit/receive antennas with Differential Unitary Space-Time Modulation (DUSTM). We propose a Reed-Solomon (RS) coded MIMO FH-CDMA transceiver as a realistic PHY framework for tactical ad hoc networks with high mobility. The proposed transceiver is robust to time-and-frequency selective fading and unknown interference, which is potentially from partial-band jamming and MAI without power control. Spatial and time/frequency diversity are achieved by DUSTM and coding/interleaving, respectively. Due to the hopping nature, interference from other users or jammers exhibit a bursty behavior. To effectively suppress such interferences, a novel receiver structure was proposed to perform joint estimation-demodulation-decoding. The proposed receiver requires no a priori knowledge about the channel and interference. Its performance in bursty interference dominated environment was shown to be robust to various practical imperfections such as the estimation error, the feedback error, and suboptimal thresholds. With the help of occasional retraining, asynchronous interference can also be suppressed. These features make it very desirable under hostile environments. The decoding error probability for EI based on effective SINR is derived analytically.

## SUMMARY OF ACHIEVEMENTS

The proposed receiver in our pervious work exhibits high near-far resistance as the decoding error probability in low signal-to-interference ratio (SIR) regime doesn't degrade as SIR decreases. This may lead to relaxed requirement on power control, which is important in distributed, open-loop networks with moderate to high mobility. Due to proper coding/interleaving and the hopping nature of the waveform, the performance of FH-CDMA systems is limited more by the distribution of the interference than by the power of the interference. This observation may hold for other systems including OFDMA with random hopping where the SINR varies significantly in a packet. In this case, conventional cross-layer design based on the average SINR within a packet may be misleading, and fundamentally different interference management schemes should be sought. For example, one implication of the high near-far resistance on network design is that the source nodes may be allowed to reach a longer distance by increasing its transmitting power. Such a strategy may be beneficial due to the reduction of number of hops required for a packet to reach its destination without seriously harm other packet transmissions when the number of nodes in the neighborhood is small compared to the available frequency slots.

Motivated by our previous work, we investigate the transmission range optimization problem for random networks with the proposed coded MIMO FH-CDMA transceiver and slotted-ALOHA MAC protocol. Increasing the transmission range may increase the length per hop and reduce the number of hops for a packet to reach its destination, thus reducing the overhead associated with routing and relaying. Conversely, since the communication media is shared in a wireless network, the multiple-access interference (MAI) limits the distance over which two nodes can reliably communicate, while short transmission range reduces interference to neighbors and allows spatial reuse. The transmission range  $R$  is also related to other network design parameters such as hop length, transmit power, average number of hops, and network connectivity.

The optimization of transmission range highly depends on the PHY and channel model. Similar problems have been studied for narrow-band networks and DS-CDMA networks with static

channels and simplistic PHY model without explicitly considering specific coding and interleaving. In contrast, our work assumes detailed PHY transceiver and realistic channel models, which account for path-loss, log-normal shadowing, and Rayleigh fading. The shadowing and fading are assumed time-varying with different time-scales due to mobility and hopping. Specifically, the fading is time-varying in each dwell according to Jakes' model. The coherence time of the shadowing is assumed at the order of a dwell (fast shadowing) or a packet (slow shadowing).

In our model, the nodes in the network are assumed to be randomly distributed on the plane according to a two-dimensional Poisson process. The nodes access the channel by slotted-ALOHA protocol and FH-CDMA with random hopping patterns. Transmit power of all nodes are assumed the same to account for the absence of power control. We optimize the transmission range with respect to the so-called information efficiency, which is equivalent to the product of the link throughput and the transmission range. Intuitively, it measures the average velocity at which a bit travels in the network per unit bandwidth.

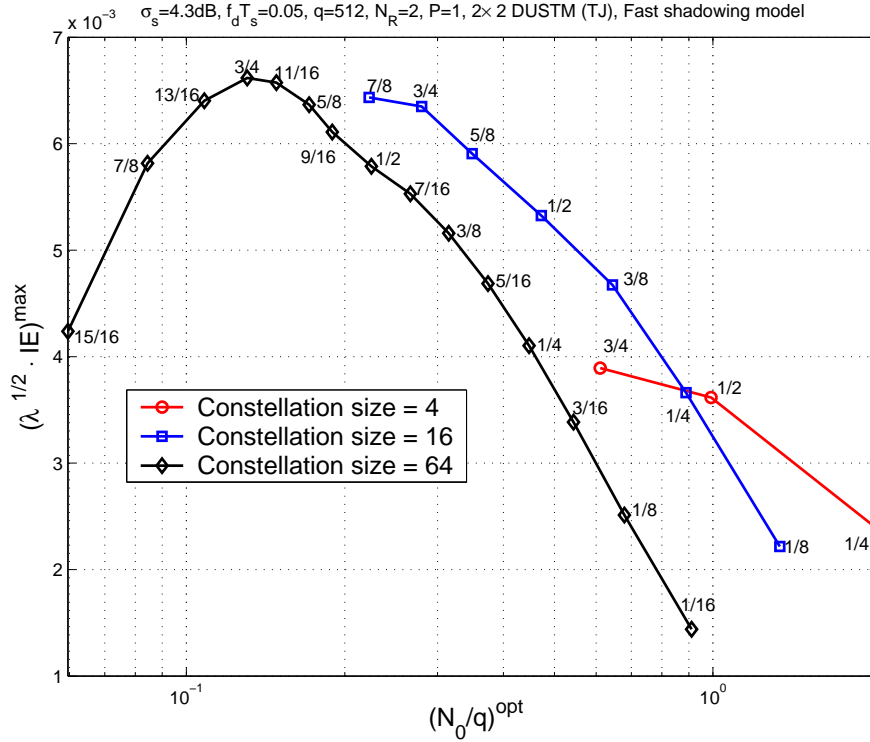
Due to hopping and the randomness of the channel, the MAI power in each dwell is a random variable, which is shown to have an alpha-stable distribution. For path-loss exponent equal to 4, the probability density function of the alpha-stable MAI power can be expressed in closed-form, thus allowing the distribution of the SIR for each dwell and the packet error probability to be derived. The optimum transmission range for maximizing information efficiency is shown to be proportional to  $\sqrt{q}$  where  $q$  is the spreading gain, while it scales as  $q^{1/4}$  in DS-CDMA networks without multi-user detection or power control. The fact that FH-CDMA scales better with spreading gain than DS-CDMA comes from the inherent "interference diversity" due to varying SIR level within a packet, which can be exploited by coding and interleaving to effectively suppress MAI. Such diversity is not available in narrow-band or DS-CDMA systems where the SIR is usually constant in a packet.

The trade-off between the information efficiency and the transmission range depends on various factors, including the modulation and coding schemes, receiver configuration, dwell length, order of spatial diversity, and channel statistics such as Doppler frequency and shadowing spread/speed. Effects of the aforementioned factors are studied in detail. Specifically, the following observations are obtained from our results.

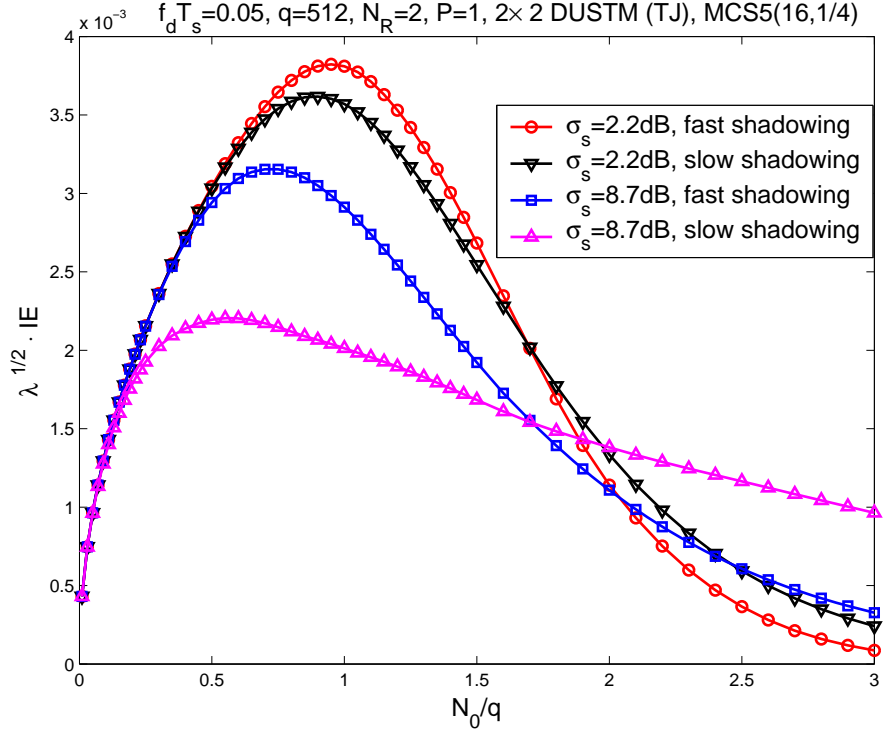
- Optimum MCSs are found for different system settings by numerical analysis, which offers guidance for adaptive transmissions from a network perspective. The optimal MCS is a function of not only the transmission range but also the channel and receiver setting (Figure 22).
- Different shadowing effects depending on the transmission range. The performance under fast shadowing is better due to higher available time diversity until the transmission range extends beyond a certain point. The resulting higher interference level can be tolerated in slow shadowing when the shadowing realization for a packet is favorable, while fast shadowing leads to inferior performance in such scenario (Figure 23).
- Whether the shadowing is fast or slow varying depends on both the shadowing coherence time and the dwell length.
- The network performance degrades as mobility increases. However, the degradation can be compensated by increasing the DFD feedback length. (Figure 24).

- Both space diversity and erasure insertion are important in improving information efficiency and extending Tx range (Figure 25).

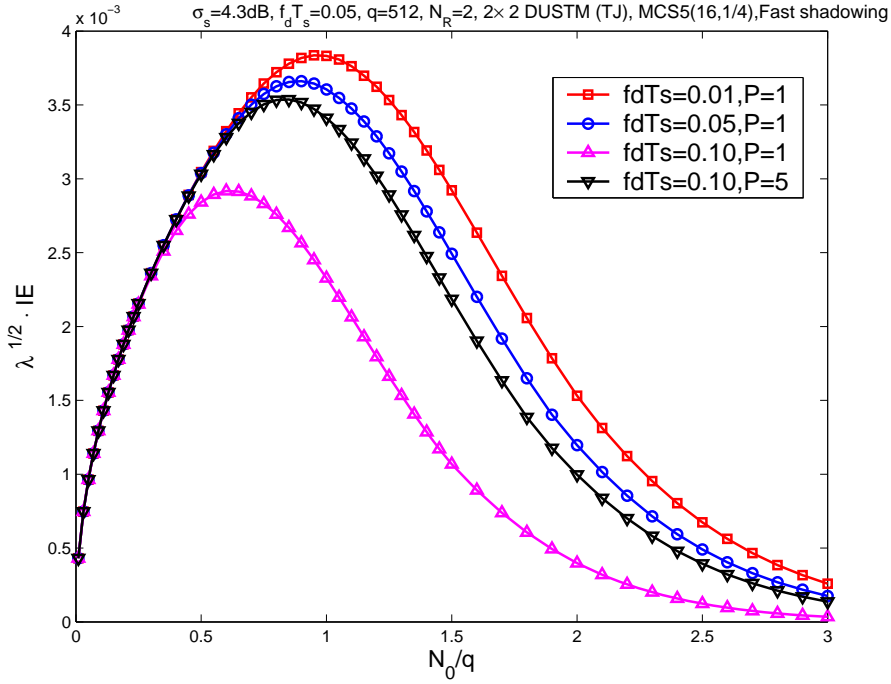
The following figures show the trade-off between the information efficiency and the transmission range. The mean of the Poisson distribution, or the node density of the network, is denoted by  $\lambda$ . The vertical axis is the information efficiency is scaled by  $\sqrt{\lambda}$ . The horizontal axis is the average number of nodes in the transmission range of a node,  $N_0 = \lambda \pi R^2$ , normalized by the spreading gain  $q$ .



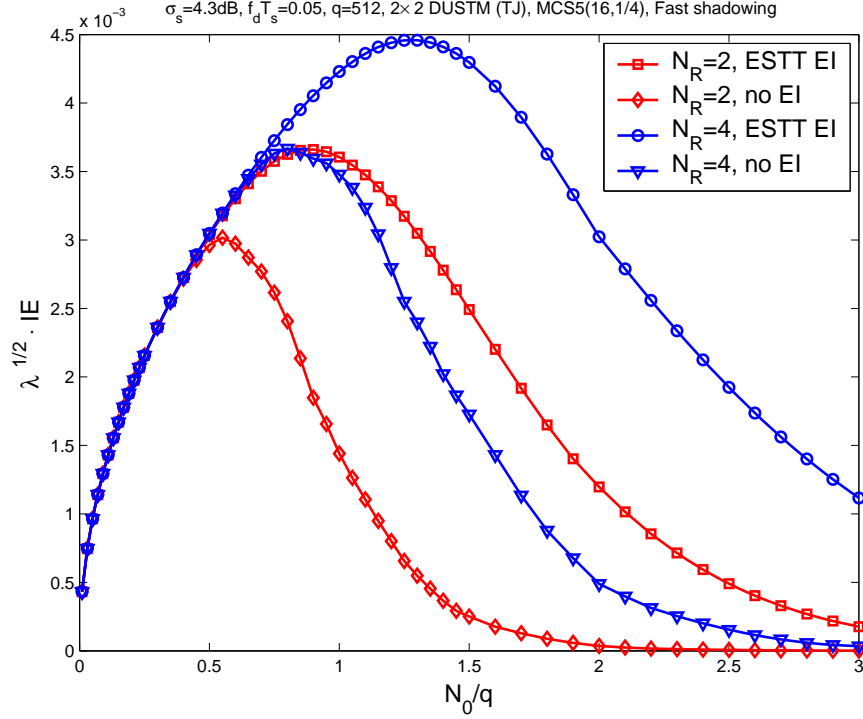
**Figure 22: Maximum scaled information efficiency  $\sqrt{\lambda}(IE)^{\max}$  versus optimum  $N_0/q$  for different constellation sizes and code rates (the number on each point indicates the Reed-Solomon code rate).**



**Figure 13: Scaled information efficiency  $\sqrt{\lambda}(IE)^{\max}$  versus  $N_0/q$  for different shadowing models ( $10\sigma_s \ln^{-1}10$  : shadowing spread in dB)**



**Figure 24: Scaled information efficiency  $\sqrt{\lambda}(IE)^{\max}$  versus  $N_0/q$  for different mobility and feedback lengths in decision-feedback demodulation ( $f_d$  : Doppler frequency,  $T_s$  : the length of a space-time block in DUSTM,  $P$  : the DFD feedback length).**



**Figure 25: Scaled information efficiency  $\sqrt{\lambda}(IE)^{\max}$  versus  $N_0/q$  for different receiver configurations ( $N_R$ : number of receive antennas, ESTT EI: effective SIR threshold test erasure insertion).**

### Future work

Our current result, although focused on transmission range and information efficiency optimization, presents a general framework of incorporating accurate PHY and realistic channel models into network design and analysis. Interesting future research topics include extending the results and insight available to analysis of ALOHA networks with FH-CDMA or OFDMA and other cross-layer optimization problems involving capacity and outage probabilities. Previous analysis on throughput/capacity/delay and decentralized retransmission control for ALOHA networks generally assumes either the multiple-packet reception model or the power capture model. Future work in these fields is required to incorporate accurate physical layer models and realistic time-varying channel models. Also, adapting the transmission range will affect the average number of hops involved in relaying a packet in ad hoc networks. This consequently relates to the delay and power consumption of the network. The relationship between the transmission range, data transmission time, and power consumption requires further investigation.

Our current results show the advantage of FH- over DS-CDMA due to the interference diversity. Compared to FH-CDMA, OFDMA achieves higher spectral efficiency by overlapping the subcarriers. However, an additional interference source in OFDMA networks with mobility is the inter-carrier interference (ICI), which arises due to Doppler frequency shift and inaccurate frequency/time synchronization. The interference diversity in OFDMA systems with hopping may also be reduced because of the cross-correlation between the ICI in different subcarriers. To



achieve accurate synchronization and suppress ICI in addition to other interference is challenging and will be investigated in mobile, multiuser OFDMA networks, especially ones with high mobility and hostile jamming.

One of the difficulties in optimizing performance in realistic communication networks is that many of the important parameters must be estimated from the data. This is a challenging problem in mobile, multiuser networks, especially ones with high mobility and hostile interference. The quality of a communication link is determined by both the channel and interference characteristics. Formulation of the channel quality information (CQI) at the receiver will be investigated based on the available statistics at the receiver for practical implementations. In Figure 25, significant gain is observed in network level results when CQI, in the form of the effective SINR, is adaptively estimated at the receiver and used in suppressing arbitrary interference without a priori knowledge. The effective SINR is related to the statistical distribution of the fading and the interference power. Generally speaking, exploiting channel state information (CSI) yields significant gain when CSI (i.e. estimates of the channel realization) is accurate, while channel distribution information (CDI) based schemes may offer consistent performance over a long time period and can be exploited at high layers in the presence of propagation delay and lag due to network layer overhead.

Future research objectives include further investigating the formulation of CQI at the receiver and exploiting CQI for interference suppression and adaptive transmission/routing under different MIMO transceiver structures. Interference suppression and adaptive transmission schemes that adapt to different forms of CQI and achieve robust optimum performance will be developed. Most currently available cross-layer designs formulate and exploit forms of CQI based on the assumption that the SINR in a packet is constant and the channel is static. This is not realistic in FH-CDMA or OFDMA with random hopping. In fact, the performance of FH systems depends more on the distribution than the mean of the SINR. Our results further suggest the necessity of adapting transmission/routing based on CQI for achieving optimum performance. Further investigation is required to extend existing cross-layer studies by accounting for such distributional information in formulating and exploiting CQI. The CQI may need to be updated as nodes change their positions or the environment varies in time. Adaptive algorithms need to be developed to track such variations and maintain accurate CQI. Efficient quantization and feedback algorithms need to be developed for CQI. Design of novel MIMO transceiver structures that adapt to the level and form of available CQI and the impact of erroneous or outdated CQI on the system performance also require further investigation.

## 6.8 Evaluation of MIMO Techniques in FH-MA Ad Hoc Networks

PI: John Proakis, James Zeidler

Graduate Student: Kostas Stamatiou

### Introduction

### Background

We consider an ad hoc network where frequency hopping (FH) and convolutional coding are employed at the physical layer, in order to mitigate multiple-access (MA) interference. FH takes place during the transmission of a packet/codeword, therefore the interference level from concurrent transmissions in the network varies across different hops/dwells; coding is then used in order to harness the available *interference diversity*. Even though not optimal, we regard this no-scheduling scenario, where the links act independently of each other, as one of practical importance and worthy of investigation. Moreover, the nodes are equipped with multiple antennas which can be used for further error protection or increase of the transmission rate, through spatial diversity or spatial multiplexing techniques, respectively.

The locations of the transmitters (TXs) in the plane are obtained by a realization of a Poisson process of density  $\lambda$  and each TX has a corresponding receiver (RX) at distance  $R$ . This model can be considered as a snapshot of a practical network where the issue of routing is neither addressed nor precluded. If  $M$  frequencies are available for hopping, then it is implied that a different fraction  $\lambda/M$  of TXs is active in each hop. We assume that the channel between each TX-RX pair over a dwell comprises path-loss, according to the law  $r^{-b}$ ,  $b > 2$ , and constant flat Rayleigh fading. The additive noise is ignored, so MA interference is the only source of noise at the RX. In each dwell, provided that the fading matrix can be estimated at the RX, the multiple antennas can be used in different ways, such as maximum-ratio-combining (MRC), space-time block coding (STBC) or spatial multiplexing (SM) via zero-forcing (ZF).

The focus of this work is to provide simple guidelines as to which of the above multiple-input multiple-output (MIMO) techniques are preferable in terms of network performance. Network performance is related to a number of intuitive network metrics previously defined in the literature. These are the *network throughput* (NT), i.e. the product  $\lambda \times T_{\text{link}}$ , where  $T_{\text{link}}$  denotes the throughput of a single TX-RX link; the *information efficiency* (IE), i.e.  $R \times T_{\text{link}}$ ; and the *transmission capacity* (TC), i.e. the maximum  $\lambda$  for which  $T_{\text{link}}$  is above a certain threshold  $1-\epsilon$ . The NT is defined for a given  $R$  and addresses the need to pack as many transmissions in space as possible, while maintaining a desirable throughput. On the other hand, the IE is defined for a given  $\lambda$  and captures the trade-off present in a multi-hop network, where transmitting farther means a packet needs fewer hops to reach its final destination, however the amount of interference in the network is increased. Finally, the TC reflects the possibility that the network poses stringent quality of service requirements, i.e., for some applications, packet losses may be unacceptable.

### Mathematical formulation

If  $c_k$  is the  $k^{\text{th}}$  transmitted packet bit (BPSK modulation), the equivalent channel model at the input of the RX decoder is

$$y_k = a_k^{1/2} c_k + w_k, \quad (1)$$

where

- $a_k$  is a chi-square random variable with  $2N$  degrees of freedom and  $N$  is the spatial diversity order of the employed MIMO scheme, e.g., for MRC, if the RX has  $m_r$  antennas, then  $N = m_r$ ; for the Alamouti code,  $N = 2m_r$ ; for SM with ZF,  $N = m_r - m + 1$ , where  $m$  is the number of active streams.
- $w_k$  is the total interference from all active TXs in the dwell. It is Gaussian, *given* its power,  $z_k$ , which is also a random variable. It can be proved that  $z_k$  follows the  $\alpha$ -stable distribution with *stability exponent*  $\alpha = 2/b$  and *scale parameter*

$$c = (\lambda \pi R^2 / M) m^\alpha \Gamma(1 - \alpha),$$

where  $\Gamma(x)$ ,  $x > 0$ , is the gamma function. The scale parameter reflects the amount of interference in the network. It is proportional to the average number of nodes within the TX radius,  $\lambda \pi R^2$ , the number of active TX antennas,  $m$ , raised to the power of  $\alpha$  and inversely proportional to the available bandwidth  $M$ .

The RX estimates  $\{a_k\}$  and  $\{z_k\}$  and decides that  $\bar{c}'$  was the transmitted codeword according to the maximum likelihood criterion

$$\bar{c}' = \arg \min_{\bar{c}} \left\{ \sum_k \frac{|y_k - \sqrt{a_k} c_k|^2}{z_k} \right\}.$$

The performance of the decoder is quantified by the frame-error-probability (FEP) (note that the terms packet, codeword and frame are used interchangeably),  $P_F$ , which is approximated by

$$P_F = \sum_{l=L, L+1, \dots} d_l P_l,$$

where  $L_c$  is the number of information bits;  $P_l$  is the probability of an error event of length  $l$ , or *pairwise error probability*;  $d_l$  is the number of error events of length  $l$  and  $L$  is the smallest possible length of an error event or the *diversity order* of the code.

The link throughput,  $T_{\text{link}}$ , of the TX-RX pair is then given by

$$T_{\text{link}} = (1 - P_F) r_{\text{code}} r_{\text{MIMO}},$$

where  $r_{\text{code}}$  is the rate of the convolutional code and  $r_{\text{MIMO}}$  is the rate of the chosen MIMO technique, e.g., for all diversity techniques,  $r_{\text{MIMO}} = 1$ , while, for SM,  $r_{\text{MIMO}} = m$ .

Instead of using a specific coding and modulation scheme to evaluate  $T_{\text{link}}$ , we can also use the *ergodic capacity*,  $C_e$ , of the channel in (1), as an upper bound to the achievable information rate. In this case,  $T_{\text{link}}$  is defined as

$$T_{\text{link}} = C_e \Gamma_{\text{MIMO}}. \quad (3)$$

The choice of the ergodic capacity as an information theoretic measure is in accordance with the fact that, through coding schemes such as convolutional coding, an averaging over different fading and interference levels takes place within the packet.

## Achievements

The statistics of the random variable  $x = a / z$  are key to our analysis. The probability density function (pdf) of  $x$  and an upper bound to its moment generating function (mgf) are derived in closed form. The mgf of  $x$  can also be evaluated accurately via numerical integration. These findings lead to the following results:

- For sufficiently small  $c$ ,  $P_l$  is upperbounded by

$$P_l \leq \left( \frac{\lambda \pi R^2}{M} \right)^l \left( m^\alpha \alpha B(N - \alpha, \alpha) \right)^l,$$

where  $B(x, y)$ ,  $x, y > 0$ , is the beta function. Also, as  $N$  increases, it holds that

$$B(N - \alpha, \alpha) \sim \Gamma(\alpha) N^{-\alpha},$$

therefore

$$P_l \leq \left( \frac{\lambda \pi R^2}{M} \right)^l \left( \left( \frac{m}{N} \right)^\alpha \Gamma(1 + \alpha) \right)^l. \quad (4)$$

- An upper bound to  $C_e$  is

$$C_e^u = \log \left( 1 + \left( \frac{\Gamma(1/\alpha + 1)^\alpha}{\Gamma(1 - \alpha)} \left( \frac{N}{m} \right)^\alpha \frac{M}{\lambda \pi R^2} \right)^{1/\alpha} \right) \quad (5)$$

and a lower bound

$$C_e^l = \frac{1}{\alpha} \log \left( \frac{1}{\Gamma(1 - \alpha) e^\gamma} \frac{1}{m^\alpha} \frac{M}{\lambda \pi R^2} \right) + 1 + \frac{1}{2} + \dots + \frac{1}{N - 1},$$

where  $\gamma = 0.5772156\dots$  is the Euler-Mascheroni constant and  $N \geq 2$ . A looser lower bound is also

$$C_e^l = \frac{1}{\alpha} \log \left( \frac{1}{\Gamma(1-\alpha)e^\gamma} \left( \frac{N}{m} \right)^\alpha \frac{M}{\lambda \pi R^2} \right) \quad (6)$$

Equations (4)-(6) reveal that  $(N/m)^\alpha$  is a determining factor in terms of coded performance and capacity. This factor introduces the intuitive notion that the spatial diversity order of a MIMO technique is effectively reduced by the number of TX antennas that transmit independent streams. As an example, consider a  $2 \times m_r$  system. The Alamouti code achieves  $N = 2m_r$ , however,  $m = 2$ , so  $N/m = m_r$ . This implies that the performance is the same as in a  $1 \times m_r$  system where MRC is used. STBC offers increased diversity but also introduces more interference in the network.

From the same equations, we observe that  $P_1$  and  $C_e^l$ ,  $C_e^u$  are increasing and decreasing functions of  $\lambda \pi R^2/M$ , respectively. This implies that there exists a value of  $\lambda$  and a value of  $R$  that maximize the NT and the IE, respectively. Substituting  $C_e$  with  $C_e^l$  in (3), the optimum value of NT over all  $\lambda$  is easily found to be

$$NT_o = \frac{1}{\alpha \Gamma(1-\alpha) e^{\gamma+1}} \left( \frac{N}{m} \right)^\alpha \frac{M}{\pi R^2} r_{MIMO} \quad (7)$$

and the optimum value of IE over all  $R$

$$IE_o = \frac{2}{\alpha \sqrt{\Gamma(1-\alpha)} e^{\gamma/2+1}} \left( \frac{N}{m} \right)^{\alpha/2} \sqrt{\frac{M}{\pi \lambda}} r_{MIMO} \quad (8)$$

When SM with ZF is the chosen MIMO technique,  $NT_o$  and  $IE_o$  can be further optimized with respect to the number of streams  $m$ . In the case of  $NT_o$ , the function to be optimized over  $m$  is

$$NT_o(m) = \frac{1}{\alpha \Gamma(1-\alpha) e^{\gamma+1}} \left( \frac{N-m+1}{m} \right)^\alpha \frac{M}{\pi R^2} m$$

We find that the optimal number of streams is  $(1-\alpha)(m_r+1)$ . However, due to the constraints  $m \in \mathbb{Z}^+$ ,  $m \leq m_r$ , where  $m_r$  is the number of TX antennas, we have

$$m_o = \min \{ \text{round} \{ (1-\alpha)(m_r+1) \}, m_r \}$$

Similarly, for  $IE_o$ ,

$$m_o = \min \left\{ \text{round} \left\{ \left( 1 - \frac{\alpha}{2} \right) (m_r + 1) \right\}, m_t \right\}$$

As an example, when  $m_t = m_r = 3$  and  $b = 4$ , or  $\alpha = 0.5$ , the optimal number of streams to be activated in terms of NT is  $m_o = 2$ , while in terms of IE it is  $m_o = 3$ .

In fig.26,  $NT_o$ , normalized by  $M/(\pi R^2)$ , is plotted vs.  $m_r$  for an  $m_r \times m_r$  system and  $\alpha = 0.5$  (in the case of MRC, it is implied that only one TX antenna is active). Note that the curves for MRC and SM with all available TX antennas are identical. Moreover, it is always better to activate only two streams than all of them at the same time.

In fig.27, the propagation constant is reduced to  $b = 3$ , therefore  $\alpha = 2/3$ . The performance of MRC is improved compared to fig.26; this is expected since  $N/m = m_r \geq 1$ , thus a smaller  $\alpha$  yields higher throughput. The opposite holds for SM with  $m = m_r$ , since  $N/m = 1/m_r \leq 1$ .

Finally, in fig.28,  $IE_o$ , normalized by  $(M/(\pi\lambda))^{1/2}$ , is plotted vs.  $m_r$  for  $\alpha = 0.5$ . The fact that the exponent of  $N/m$  in (8) is  $\alpha/2$  changes the trends compared to when NT is the choice of network metric, e.g. transmitting with all TX antennas is optimal for up to  $m_r = 5$ .

## Future work

Based on the assumption of a random Poisson network, where interference from concurrent transmissions is mitigated with FH and coding, we developed an analytical framework to evaluate different single-user MIMO techniques. Simple expressions were derived that indicate the impact of employing a specific MIMO technique on network metrics of interest.

Future research will focus on the following main topics:

- Multi-hop networks: studying a multi-hop network is directly related to routing and power control. We propose to evaluate the impact of single-user MIMO techniques under different routing and power control strategies and an ALOHA MAC protocol. An appropriate network metric for a multi-hop network is the *spatial density of progress*. It is defined as the mean total distance traveled in one hop by all transmissions in some unit area and thus provides a compromise between the NT and IE metrics defined in section 2.1.
- Imperfect channel state information (CSI) at the RX: the fading matrix and interference power in each dwell are parameters that have to be estimated for ML decoding. In this work, we have assumed that they are perfectly known. What is the impact of imperfect CSI on the performance, when ML or Bayesian estimation methods are employed to estimate the unknown parameters?
- Multi-user MIMO and scheduling: using the Poisson random network assumption, we propose to characterize the network performance when some form of cooperation is present between the nodes, either in the form of multi-user MIMO processing or scheduling. The simplest scenario to be examined is cooperation between the two closest

interfering nodes. As we did in our work to date, our objective is to derive tractable analytical expressions for the network metrics, which provide insight and lend themselves to optimization.

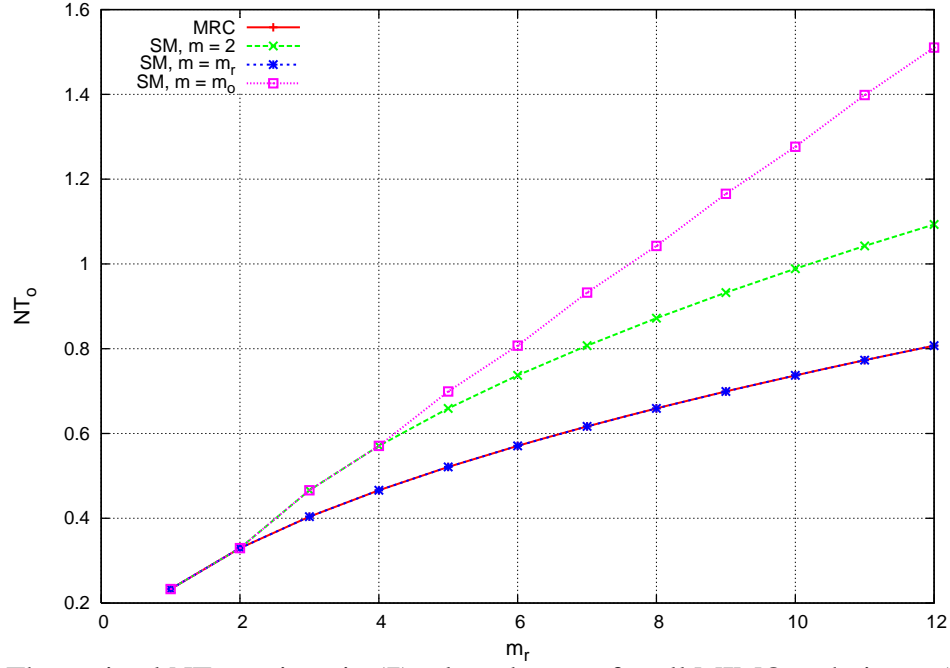


Fig.26 - The optimal NT, as given in (7), plotted vs.  $m_r$  for all MIMO techniques ( $\alpha = 0.5$ ).

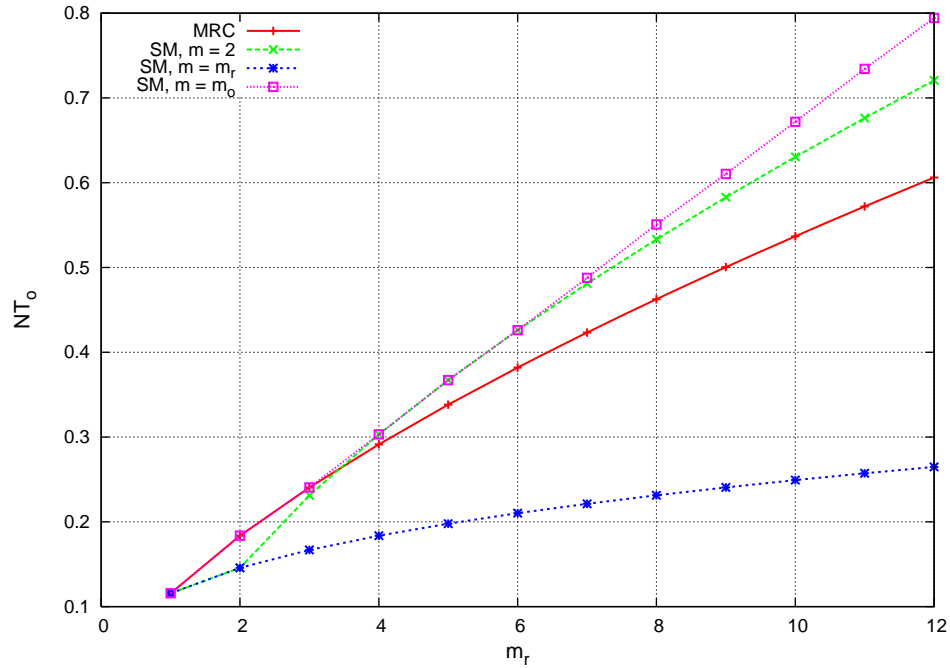


Fig.27 - The optimal NT, as given in (7), plotted vs.  $m_r$  for all MIMO techniques ( $\alpha = 2/3$ ).

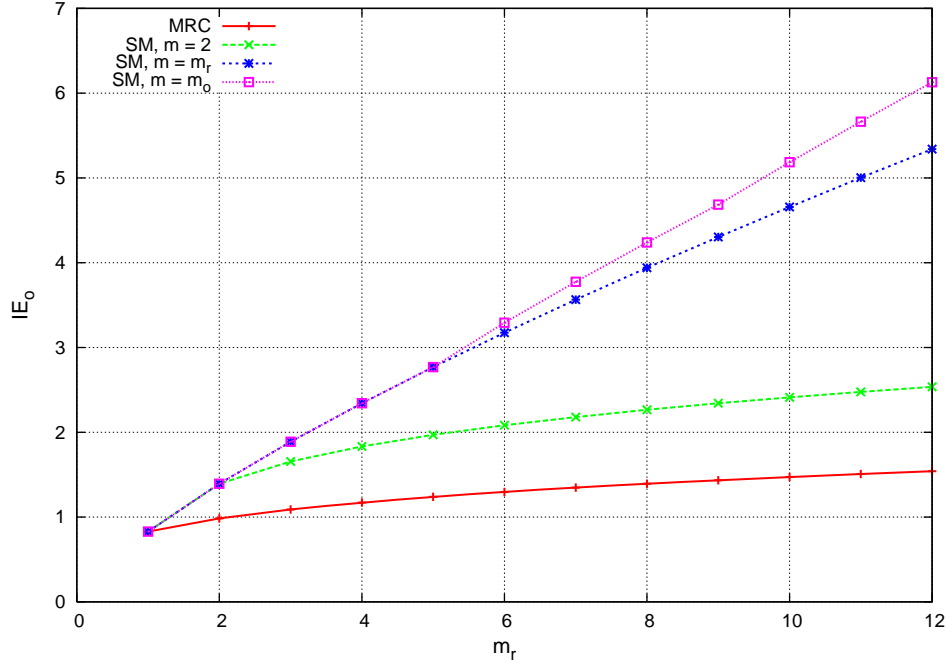


Fig.28 - The optimal IE, as given in (8), plotted vs.  $m_r$  for all MIMO techniques ( $\alpha = 0.5$ ).

## 6.9 Using Noisy Quantized Feedback in MIMO Systems

PI: Hamid Jafarkhani

We have had contributions in two research projects:

- (1) MIMO systems using finite-rate noisy feedback
- (2) Network Beamforming

In the following we briefly summarize our progress with both projects:

(1) Combining the benefits of the diversity/coding gain from space-time coding and the array gain from beamforming has recently attracted a lot of attention. From a practical point of view, the transmitter channel state information is degraded by several factors in the feedback channel, e.g. the bandwidth limitation, the delay, and the noise. We consider the effects of a finite-rate feedback and the noise in the feedback link. So far, we have considered the effects of limited bandwidth in the feedback link and also the noise in the feedback link. We have considered several models for the noise in the feedback link. We consider a simple discrete memoryless channel, a finite-state channel, and a reciprocal fading channel. Also, we have considered several design criteria for optimizing the combination of beamforming and space-time coding. We consider pairwise error probability, the source distortion for transmission of multimedia signals, and outage probability as design criteria. The main contributions are:

### A. Space-Time Coding and Beamforming Using Noisy Rate-Limited Feedback



We combine space-time coding and transmit beamforming over quasi-static block fading MISO channels, using quantized channel feedback. Our goal is to preserve diversity and besides, to provide additional array gain (SNR gain) compared to conventional space-time codes. In practice, the transmitter channel state information is degraded by bandwidth limitation and noise in the feedback link. The imperfect and impaired feedback leads to drastic performance degradation unless the system is robustly designed against low-resolution and erroneous feedback information. Therefore, combining coding and beamforming must be optimized for low-rate and erroneous feedback conditions. In this work, the combining is performed using a class of constellation sets inspired from orthogonal designs and precoded STBCs which is called partly precoded orthogonal designs (PPODs). PPODs provide full-diversity with any feedback rate, any number of transmit antennas, and any amount of feedback error. The attractive property of our scheme is that it converges to conventional space-time coding with low-rate and highly erroneous feedback and to pure beamforming with high rate and error-free feedback. Moreover, our scheme shows desirable robustness against design mismatch with respect to feedback channel specifications. [14] We also study the problem of maximizing the expected rate over a slowly fading channel with quantized channel state information at the transmitter (CSIT). This problem has been recently studied in the literature assuming a noiseless feedback link. In this work, we consider a more realistic model, where the feedback link suffers from fading, as well as the limited power allocated to the feedback signals. Our scheme considers a finite-state model to capture the fading in the feedback link. We solve the rate maximization problem with different power control strategies at the transmitter. A channel optimized scalar quantizer (COSQ) is designed to incorporate feedback in our transmission scheme. Unlike the conventional COSQs where the objective is to reconstruct the source, our proposed quantizer is designed to optimize the expected rate of the forward link. For a high quality feedback channel, the proposed COSQ performs close to the noiseless feedback case, while its performance converges to the no feedback scenario as the feedback channel quality degrades. [15]

## **B. Joint Source-Channel Coding for Quasi-Static Fading Channels with Noisy Quantized Feedback**

When the transmitted source is multimedia information and not data, minimizing the pairwise error probability or the bit error probability is not the best design criterion. In such a case, usually a distortion measure which is appropriately picked based on the nature of the transmitted signal should be minimized. Also, the nature of the coding problem is different and the analysis looks like a rate-distortion analysis. For example, let us consider the transmission of a Gaussian source over a single-input multiple-output (SIMO) quasi-static fading channel. The goal is to minimize the expected distortion of the reconstructed signal at the receiver. We consider a delay-limited scenario where channel coding is restricted to a single realization of the channel. Channel state information (CSI) is assumed to be known perfectly at the receiver, and a zero-delay, noiseless, fixed-rate feedback link provides a quantized version of the CSI to the transmitter. An upper bound on the performance is derived and it is shown that for practical values of the channel signal to noise ratio (SNR), this bound can be achieved with a very limited knowledge of the channel quality. We show that unlike the rate maximization problems, temporal power adaptation at the transmitter provides significant gains, and the amount of the gain heavily depends on the bandwidth expansion ratio. For asymptotically high SNRs, we derive the

distortion exponent of the system, defined as the slope of the expected distortion with respect to the channel SNR. We show that the distortion exponent of limited feedback is equivalent to that of superposition coding without feedback, so long as the number of quantization levels in the feedback scheme is equal to the number of the layers in the superposition coding scheme. For the finite-SNR regime, we propose an optimal and efficient numerical technique to design the feedback scheme. [17] A similar problem can be considered when the feedback channel is noisy. In this case, the goal is to minimize the expected distortion of the reconstructed signal at the receiver considering the finite rate of the feedback link and the errors in the feedback link. A delay-limited scenario is assumed where channel coding is restricted to a single realization of the channel. Quantized channel state information at the transmitter (CSIT) is obtained using a noisy, fixed-rate feedback link and is used to adjust the transmission rate and power. A channel optimized scalar quantizer (COSQ) is designed to incorporate the effects of the errors in the feedback link. For a high quality feedback channel, the proposed COSQ performs close to the noiseless feedback case, while its performance converges to the no-feedback scenario as the feedback channel quality degrades. We show that noisy feedback does not improve the performance at asymptotically high signal to noise ratios (SNRs). Nevertheless, the numerical results for a Rayleigh fading channel show that noisy feedback provides significant gains for practical values of the SNR. [18] One advantage of such a system is that the system automatically adopts itself to the level of the noise in the feedback channel. In fact, when there is no noise, the system converges to the optimal system using a noiseless feedback link. Also, as the noise in the feedback system is increased, the system converges to an open-loop system with no feedback. In other words, one attractive property of the proposed solution is that the system automatically converges to space-time coding in the extremely poor feedback case and beamforming in the high quality feedback case.

### **C. Outage Behavior of Quasi-Static Fading Channels with Partial Power Control and Noisy Feedback**

We investigate the outage behavior of multiple antenna slowly fading channels with resolution constrained feedback and partial power control. A fixed-rate communication scheme is considered. It is known from the literature that with error-free feedback, the power control codebook that minimizes the outage probability with an average power constraint at the transmitter has a circular quantizer structure. Moreover, the diversity gain of the system increases polynomially with the cardinality of the power control codebook. Here, we study a similar system, but within a noisy feedback channel framework. We show that the optimal quantizer structure in this scenario is still circular. With noisy feedback, using the new power control codebook, the outage performance of the system is superior to that of a no-feedback system. However, we show through asymptotic analysis that the diversity gain is the same as a no-feedback scheme. [19]

(2) In this work, we introduce the concept of beamforming in wireless relay networks. First, we consider perfect channel information at relays, the receiver, and the transmitter if there is a direct link between the transmitter and receiver. It is assumed that every node in the network has its own power constraint. A two-step amplify-and-forward protocol is used, in which the transmitter and relays not only use match filters to form a beam at the receiver but also adaptively adjust their transmit powers according to the channel strength information. For a network with any

number of relays and no direct link, the optimal power control is solved analytically. [16] The complexity of finding the exact solution is linear in the number of relays. Our results show that the transmitter should always use its maximal power and the optimal power used at a relay is not a binary function. It can take any value between zero and its maximum transmit power. Also, surprisingly, this value depends on the quality of all other channels in addition to the relay's own channels. Despite this coupling fact, distributive strategies are proposed in which, with the aid of a low-rate broadcast from the receiver, a relay needs only its own channel information to implement the optimal power control. Simulated performance shows that network beamforming achieves the maximal diversity and outperforms other existing schemes. Then, beamforming in networks with a direct link are considered. We show that when the direct link exists during the first step only, the optimal power control at the transmitter and relays is the same as that of networks with no direct link. For networks with a direct link during the second step only and both steps, recursive numerical algorithms are proposed to solve the power control problem. Simulation shows that by adjusting the transmitter and relays' powers adaptively, network performance is significantly improved. Currently, we are working on relaxing the channel state information needed at the relay. We are considering a statistical knowledge, for example mean or covariance and a quantized limited rate feedback. The main challenge in all such scenarios is to find an optimal algorithm that solves the problem in a distributed way. Although such a network behaves like a virtual MIMO, different nodes do not have information about each other and only distributed algorithms are practical.

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## **6.10 Impact of Quantization, Channel Estimation, and Delay on Feedback MIMO Systems**

### **Rate Related Feedback in MIMO Systems: Theoretical Bounds**

**PI: Bhaskar D. Rao**

**GSRs: Jun Zheng and Yogananda Isukapalli**

#### **SUMMARY OF RESEARCH**

Our work is concerned with feedback based MIMO systems; development of effective quantization methods, analysis of feedback systems with finite rate feedback, analysis of feedback systems with imperfect channel state information, and effective use of feedback in ad-hoc networks, We now describe our progress in these and highlight our specific research contributions.

#### **a) Capacity Analysis of MIMO Systems using Limited Feedback Transmit Precoding Schemes**

In this work we employ a high resolution quantization framework to study the effects of finite-rate feedback of the channel state information (CSI) on the performance of MIMO systems over i.i.d. Rayleigh flat fading channels. The contributions of this work are twofold. First, we extend the general distortion analysis of vector quantizers to deal with complex source variables. Necessary and sufficient conditions that guarantee a concise high-resolution distortion analysis in the complex domain is presented. Second, as an application of the proposed complex distortion analysis, tight lower bounds on the capacity loss due to the finite-rate channel quantization are provided for MIMO systems employing a fixed number of equal power spatial beams. Based on the obtained closed-form analytical results, it is shown that the system capacity loss decreases exponentially as the ratio of the quantization rate to the total degrees of freedom of the channel state information to be quantized. Moreover, MIMO CSI-quantizers using mismatched codebooks that are only optimized for high-SNR and low-SNR regimes are also investigated to quantify the penalties incurred by the use of mismatched codebooks. In addition, the analysis is extended to deal with MIMO systems using multi-mode spatial multiplexing transmission schemes with finite-rate CSI feedback. Finally, numerical and simulation results are presented which confirm the tightness of the derived theoretical distortion bounds. The details can be found in our publication [5].

#### **b) Spatially correlated channels with ideal channel estimation and no-delay**

In [1], the problem of quantifying the loss due to finite rate quantization, is studied from a source coding perspective by formulating the finite-rate quantized MISO system as a general vector quantization problem with encoder side information, constrained quantization space and non-

mean-squared distortion function. By utilizing the high-resolution distortion analysis of the generalized vector quantizer, tight lower bounds of the ergodic capacity loss of a quantized MISO system over i.i.d and correlated fading channels with both optimal and mismatched channel quantizers were obtained. The details can be found in our publication [2].

The general framework developed in [1], is versatile and has the potential for being adapted to deal with a variety of problems. The methodology, with suitable modifications, is used to enable the distortion analysis of a wide class of vector quantizers with transformed codebooks. *Transformed codebooks* are often obtained by a transformation of a given codebook, potentially optimum for a particular set of statistical conditions, to best match the statistical environment at hand. The procedure, though suboptimal, has recently been suggested for CSI feedback-based multiple antenna systems because of their simplicity and effectiveness. In the existing literature, limited analytical results are available characterizing the performance of transformed channel quantizers for multiple antenna systems with finite-rate feedback. We focus our attention on investigating the effects of codebook transformation on the performance of multiple antenna systems with finite-rate CSI feedback. The contributions of this work are twofold. We first consider the general problem of analyzing a vector quantizer with transformed codebook. Bounds on the average system distortion of this class of quantizers are provided. It exposes the effects of two kinds of sub-optimality introduced by the transformed codebook on system performance, which include loss caused by the sub-optimal point density as well as loss due to the mismatched Voronoi shape. We then focus our attention on the application of the proposed general framework to providing capacity analysis of a feedback-based MISO system with spatially correlated fading channels using channel quantizers with transformed codebooks. In particular, using system capacity as the objective function, upper and lower bounds on the average distortion of MISO systems with transformed codebooks are provided and compared to that of the optimal channel quantizers. The details can be found in our publication [4].

Average SEP, another important system performance metric, for limited set of constellations has been studied with i.i.d fading channels based on approximating the statistical distribution (pdf) of the key random variable (as a truncated beta distribution) that characterizes the system performance. This pdf is used to study effect of quantization on average SEP for limited constellations. Similar to the capacity analysis, SEP analysis for correlated channels using such statistical methods have not met with much success. In this work we make use of the source coding based framework developed in [1] to study the average SEP loss (loss only) in correlated Rayleigh fading channels with rectangular M-QAM constellation. Assuming perfect channel estimation, no-feedback delay and error-less feedback, for spatially i.i.d and correlated channels we derive analytical expressions for loss in average SEP due to finite-rate channel quantization. We then consider the high-SNR regime and show that the loss associated with correlated case is related to the loss associated with the i.i.d case by a scaling constant given by the determinant of the correlation matrix. We also conduct simulation results in support of the analytical expressions. We are now extending this work to calculate the loss in BEP for rectangular M-QAM and M-PSK constellations. The application of the theory in [1] to this problem is quite involved because of the complicated dependency of the objective function on the random variables involved and the results derived here serve to validate the general nature of the theory [1]. In addition, the results provide interesting insight into the more general and useful scenario

of correlated channels with a more practical and relevant measure. The details can be found in our publication [7].

### **c) Spatially i.i.d channels with estimation errors and feedback delay**

The work so far has considered only the impact of quantization on feedback based MIMO systems. In reality there are additional types of imperfection in these systems such as estimation error and delay. Some research works have considered some aspects of these imperfections. The existing related literature considered either BPSK (or QPSK) with estimation errors, no feedback delay and perfect quantization, or ideal channel estimation with finite-rate quantization for general modulations, combined effects of various channel imperfections for general modulations is not yet investigated. A model that can captures the three forms of feedback related imperfections, i.e. estimation, delay and quantization, is not available. This contribution is targeted to fill in this important void.

In this work, we present a general framework for the performance analysis of transmit beamforming for MISO systems on Rayleigh fading channels with imperfect channel feedback. The feedback imperfections are characterized in terms of noisy channel estimation at the receiver side, quantization of CSI, and feedback delay. This formulation is shown to be applicable for any linear two-dimensional modulation scheme on spatially i.i.d Rayleigh fading channels. Our analytical framework encompasses three popular MISO system models, namely, frequency-domain duplexing (FDD) systems, FDD with finite rate quantization of CSI systems, and time-domain duplexing systems. We analyze average symbol error probability and bit error probability performances of M-PSK and M-ary rectangular QAM constellations with Gray code mapping. Our numerical and simulation results show that channel estimation inaccuracy and feedback delay are more detrimental to the system performance compared to the effects of finite-rate channel quantization. The details can be found in our publications [3], [8] and [9].

### **d) Spatially correlated channels with estimation errors and delay**

As described above, we have developed a model that captures the three forms of imperfection in a feedback MISO system. The imperfections are the estimation errors at the receiver, feedback delay and channel quantization, but the channel was assumed to be spatially i.i.d. The modelling and further analysis become complicated once the spatially i.i.d channel assumption is replaced with spatially correlated channel.

In this work, for spatially correlated channel with estimation errors and feedback delay, a model that captures estimation errors, feedback delay, and finite-rate quantization of channel is developed. A novel codebook design algorithm that is directly related to reducing the loss in ergodic capacity of a spatially and temporally correlated channel with estimation errors and delay (EED) is proposed. Analysis for the loss in ergodic capacity is presented for spatially i.i.d channels with EED. Simulation results show that the new codebook designed under the consideration of estimation errors and feedback delay clearly outperforms the codebook designed

under ideal conditions. The loss analysis of spatially i.i.d channels is also validated through computer simulations. The details can be found in our publication [10].

#### **e) Channel Modeling and Feedback Delay**

In all the above mentioned work we clearly show that the effect of delay and estimation errors is detrimental to system performance. Increasing the pilot SNR of training symbols can reduce the estimation error, however delay is a serious problem and it is fundamentally different from estimation errors. To combat delay we are approaching the problem in two directions, one is prediction of the channel and the other is developing a different system model such that the delay impact is minimized. The idea behind the channel prediction is that the receiver feeds back the predicted version of the channel rather than the actual channel.

In the work on channel prediction, we study the role of ergodicity in wireless channel prediction. Following the sinusoidal channel model, conditions under which the ergodic assumption is valid are presented. This sheds insight into when statistical channel models that employ ensemble averaging are appropriate. Due to the lack of ergodicity in a typical real world wireless channel, Least Squares prediction, an approach based on time averages is motivated as opposed to linear minimum mean squared error channel prediction, an approach based on ensemble averaging. We then study methods such as Forward-Backward and rank reduction for high quality channel prediction. The details can be found in our publications [6] and [9].

#### **f) MAC Protocols for MIMO Ad-Hoc networks**

We have begun working on developing MAC protocols for MIMO Ad-Hoc Networks. The use of space-time block codes in ad-hoc networks has received some attention. The advantage of such a scheme is that one can benefit from the spatial diversity without significantly impacting the spatial spectral characteristics. The use of feedback has proven to be more complex. In our work, we are examining the use of selection diversity in ad-hoc networks. This has the advantage of simplicity and robustness. Full spatial diversity is achieved and it also allows for multi-user diversity. In addition, there are additional benefits/differences compared to a cellular kind of network. In a multi-user cellular network, the channels of all the intra cell users are optimized. This means the interference can be quite high. In an ad-hoc network, since many Tx-Rx pairs are involved, only the desired user is optimized while the interference profile is not altered. This can lead to higher system throughput. A practical protocol to test the pros and cons of selection based MIMO ad-hoc networks is being designed and will be reported in the near future.

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## **6.11 Channel Estimation Performance Bounds in Time- and Frequency- Selective Fading Environments**

**PI: A. Lee Swindlehurst**

**GSRs: Matthew Nogleby (50%, MS student), Michael Larsen (50%, Ph.D. student)**



## SUMMARY OF TECHNICAL ACCOMPLISHMENTS

Our work during this period has focused primarily on two projects: (1) a continuation of our earlier work on performance bounds for channel estimation, and (2) a new joint project with MURI colleagues at the University of California at Riverside on cooperative power allocation strategies in MIMO wireless networks. The following two paragraphs summarize our work in these two areas; details for each project are then provided in the sequel.

1. Performance Bounds for Channel Estimation: In all wireless communication systems, channel estimates are obtained periodically in time depending on the availability of training data, and also at various different frequencies in wideband networks where, for example, OFDM schemes are employed. Since the detection performance of any link is critically dependent on the accuracy of the channel estimate employed, it is important to understand how the quality of a given estimate will degrade depending on how long ago it was obtained or how “far away” in frequency it is to be applied. In this work, we calculate channel estimation performance bounds for such scenarios, including the effects of different model parameterizations and array calibration errors. The results indicate that spatial signature-based channel models provide a reasonable trade-off between performance and model sensitivity.

2. Cooperative Power Allocation Strategies: Networks composed of nodes with multiple antennas offer the possibility of significantly higher throughput. However, as a node seeks to maximize the data rate across its own link, it typically generates increased interference, decreasing the rates across other links. In this work, we have considered an ad-hoc network composed of point-to-point multiple-input multiple-output (MIMO). Previous approaches, which focus on maximizing either individual or total network throughput, may result in inefficient or unfair solutions. On the other hand, our approach is based on the Nash bargaining solution from cooperative game theory. Theoretical and empirical results show that this approach efficiently balances individual user rates and total network throughput.

### **1. Channel Estimation Performance Bounds in Time- and Frequency-Selective Fading Environments**

The most common way for a receiver to obtain channel information is through the insertion of known pilots, or training data, in the transmitted signal. When the transmitter, receiver, or both are moving, the channel will exhibit temporal fading, and if the wireless system is wideband, the channel may also possess frequency selectivity. In such cases, the channel is usually estimated through training data interspersed at different times and frequency bands. Once the channel is estimated at the time-frequency locations of the pilot symbols, the estimates at the remaining times and frequencies are found using interpolation and/or extrapolation. Extrapolation in time, or prediction, is particularly useful in bridging the gap between the channel estimates and the current channel state for adaptive modulation and power control.

In both channel estimation and prediction, it is useful to quantify the best possible performance that may be expected as a standard for evaluating various estimation and prediction techniques.

Also, it may indicate characteristics that are useful or necessary for optimal estimation and prediction performance. We have studied the theoretical performance of pilot-based channel interpolation and prediction for frequency-selective, time-fading, wireless MIMO channels via bounds for the interpolation and prediction error of the channel. These bounds are particularly suited to MIMO orthogonal frequency division multiplexing (MIMO-OFDM) systems, a popular technique for frequency-fading wideband scenarios. Analysis of these bounds demonstrates that (1) better interpolation and prediction performance can be obtained using MIMO systems, (2) parametric channel modeling is advantageous in terms of estimation performance, and (3) correlations between model parameters are important for achieving the interpolation and prediction error bound.

Our analysis is based on three related parametric channel models. The lower bounds on interpolation and prediction error for each model are derived using a vector formulation of the Cramér-Rao Bound (CRB) for functions of parameters. For each of the models, we assume interpolation and prediction are carried out by estimating the channel parameters and then using those estimates with the model to interpolate and extrapolate the channel. However, the bounds are valid even when other estimation techniques are employed. The first model is an extended ray-based parametric channel model for SISO and MIMO channels, given as

$$\mathbf{H}(\omega, t) = \sum_{l=1}^L \alpha_l \mathbf{a}_{r,l}(\theta_{r,l}) \mathbf{a}_{t,l}^T(\theta_{t,l}) \exp\{j(\omega_c - \omega)\tau_l + jw_{d,l}t\}$$

where  $L$  indicates the number of paths through which the signal travels (multipath),  $\alpha_l$  is the loss coefficient of path  $l$ ,  $\mathbf{a}_t(\theta_{t,l})$  and  $\mathbf{a}_r(\theta_{r,l})$  are the transmit and receive array responses of path  $l$ , which depend on the directions of departure (DOD) and directions of arrival (DOA) of each multipath signal component. In the equation,  $\omega_c$  is the center or reference frequency of our bandwidth of interest,  $\tau_l$  is the delay of path  $l$ , and  $w_{d,l}$  is the Doppler frequency of path  $l$ . We call this the DOD/DOA model. If we assume that the array responses do not depend on direction of arrival (DOA) and direction of departure (DOD), but are, instead, spatial signatures (SS), we obtain a more general vector spatial signature (VSS) model

$$\mathbf{H}(\omega, t) = \sum_{l=1}^L \mathbf{a}_{r,l} \mathbf{a}_{t,l}^T \exp\{j(\omega_c - \omega)\tau_l + jw_{d,l}t\}.$$

Finally, if we assume, that instead of transmit and receive array responses for each path, there is simply a matrix describing the behavior of each path, we obtain the matrix SS (MSS) model

$$\mathbf{H}(\omega, t) = \sum_{l=1}^L \mathbf{A}_l \exp\{j(\omega_c - \omega)\tau_l + jw_{d,l}t\}$$

The MSS model may be thought of as a generalization of the finite impulse response (FIR) channel model commonly used in the literature to represent wideband MIMO channels.

Figures 29 and 30 below are plots of slices of the error bounds in frequency and time, respectively, for a two-path channel model. The channels were generated by simulation according to the ray-based model assuming three antennas at both the transmitter and receiver. The bounds are averaged over 100 channel realizations. The simulations assume  $N$  channel samples are available for the parameter estimation. These samples are corrupted with additive white Gaussian noise with a variance of -20 dB. Note that the same channel realizations and samples were used to generate all of the bounds. The bounds demonstrate that if the channel is

well modeled by the ray-based channel model, using the simpler spatial signature models (including the common FIR model) to interpolate and extrapolate the channel results in a significant degradation of the possible channel estimation performance. Also included in the plots are additional bounds for the DOD/DOA model that assume the antenna arrays have calibration errors. When the calibration errors are large enough, the advantages of the DOD/DOA model are lost.

## 2. Cooperative Power Scheduling for Wireless MIMO Networks

Managing the mutual interference between nodes in a MIMO wireless network is crucial to realizing their potential throughput advantages. In maximizing the data rate across its own link, a transmitter interferes with other network transmissions, decreasing the throughput possible across those links. This results in a trade-off between individual data rates and total network throughput. In this paper we focus on finding a solution that provides a fair and efficient balance between these two competing objectives.

We focus on wireless network consisting of  $L$  point-to-point links; that is there are  $L$  unique source nodes and  $L$  unique destination nodes. We consider the mutual information—which gives an upper bound on the data rate—across each of these links. Each source node  $i$  transmits a complex baseband vector  $\mathbf{x}_i$ , which we model as a zero-mean Gaussian random vector with covariance matrix  $\mathbf{P}_i = E\{\mathbf{x}_i \mathbf{x}_i^H\}$ . We model the power constraint on each transmitter by a constraint on the trace of the covariance matrix  $\mathbf{P}_i$ . The transmitted vector is passed through the channel, and is corrupted by additive white Gaussian noise as well as interference from other transmitters. Defining  $\mathbf{H}_{i,j}$  as the channel matrix between the  $j$ th source node and the  $i$ th destination node, the interference covariance at the  $i$ th receiver due to the other  $L-1$  transmitters is

$$\mathbf{R}_i = \sum_{\substack{j=1 \\ j \neq i}}^L \mathbf{H}_{i,j} \mathbf{P}_j \mathbf{H}_{i,j}^H.$$

The mutual information across the  $i$ th link is given by

$$I_i = \log_2 \frac{|\mathbf{H}_{i,i} \mathbf{P}_i \mathbf{H}_{i,i}^H + \mathbf{R}_i + \mathbf{I}|}{|\mathbf{R}_i + \mathbf{I}|} \text{ (bits/sec/Hz),}$$

where  $|\mathbf{A}|$  represents the determinant of the matrix  $\mathbf{A}$ . Finding the covariance matrix that maximizes the mutual information for a single link has been solved for many years.

Several different approaches have been taken for finding the optimum approach for networks of interfering links. In one approach, each source node iteratively maximizes the mutual information across its own link, assuming that the interference covariance from other users is held constant. Iterations continue until no single transmitter can improve its mutual information by changing its transmit covariance  $\mathbf{P}_i$ . In game-theoretic terms, this solution is a (non-cooperative) *Nash equilibrium*, and is optimal from an individual standpoint in that no single user can improve its mutual information. However, individual maximization typically leads to an inefficient solution, especially if interference is strong among links. Therefore, methods have been proposed to find source covariance matrices that maximize the *sum* mutual information

through the network, rather than optimizing each link individually. However, while this method gives an efficient solution in terms of total throughput, it often results in an unfair allocation of resources. When interference is strong, the optimal solution typically shuts down weaker links so that the stronger links can transmit without interference, which may be undesirable in a wireless network.

To overcome these difficulties of inefficiency and unfairness, we approach the problem somewhat differently. First, we divide up the transmission time into  $L$  time slots over which the source nodes may use different covariance matrices. We then consider the *average* mutual information across each link, which is given by

$$\bar{I}_i = \frac{1}{L} \sum_{t=1}^L \log_2 \frac{|\mathbf{H}_{i,i} \mathbf{P}_i(t) \mathbf{H}_{i,i}^H + \mathbf{R}_i(t) + \mathbf{I}|}{|\mathbf{R}_i(t) + \mathbf{I}|} \text{ (bits/sec/Hz),}$$

where  $\mathbf{R}_i(t)$  is the interference covariance at the  $i$ th receiver during time block  $t$ . This time-varying structure allows us degrees of *temporal* freedom that we may exploit in addition to the spatial degrees of freedom allowed by the MIMO channels.

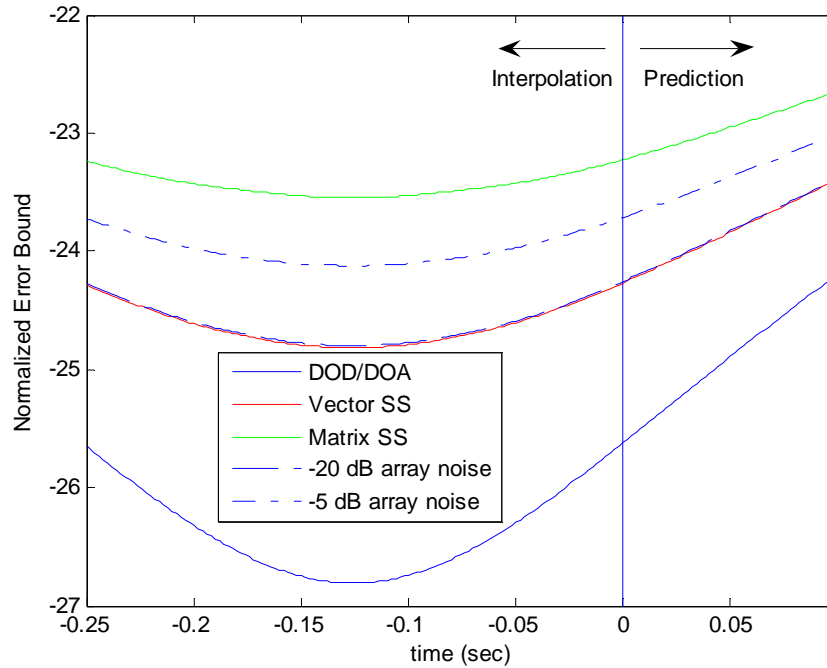
We also implement a result from cooperative game theory known as the *Nash bargaining solution* (NBS). In general, the Nash bargaining solution defines a solution to a resource allocation problem that is efficient, but still considers the payoff to individual players. It assumes that players may collaborate and cooperate in making a joint decision. For simplicity, we explain the Nash bargaining solution in terms of our MIMO network problem. Define the vector *disagreement point*  $\delta$ , which represents the “status quo,” or the rate across each link should bargaining fail. We use the non-cooperative Nash equilibrium solution described above as the disagreement point. The Nash bargaining solution is defined by four axioms, which we do not discuss in detail: Pareto efficiency, Independence under positive affine transformations, Symmetry, and Independence of irrelevant alternatives. Pareto efficiency guarantees an efficient solution, and the symmetry axiom guarantees—at least in one sense—a fair solution.

Nash showed that a solution complies with these four axioms if and only if it maximizes the product (known as the *Nash product*)

$$\psi = \prod_{i=1}^L (\bar{I}_i - \delta_i).$$

Thus, the Nash bargaining solution defines an objective function  $\psi$  which we must maximize. Using the well-known gradient projection algorithm, we solve for feasible covariance matrices that constitute a local maximum of the Nash product. To empirically evaluate the performance of the Nash bargaining approach, we simulate using Rayleigh fading channels with a variety of signal- and interference-to-noise ratios. We let  $L=6$  and let each node have three antennas. In Figure 31, the SNR across each link is 15dB and the INR is the same among all links. In Figure 31 we show the *minimum* mutual information—or the mutual information across the worst link—comparing the NBS to other approaches, averaged over 1000 independent trials for each data point. Notice that as interference becomes stronger, the worst-case mutual information quickly approaches zero for most approaches. However, the NBS, giving a fair solution, maintains non-zero mutual information across even the weaker links.

In Figure 32 we let the SNRs and INRs be independently and uniformly distributed (in dB) across the interval  $[0,35]$ . We show the empirical distribution function of the mutual information across the links, taken over 1000 sets of channel realizations. The maximum throughput approach gives the highest mean (6.70 bits/sec/Hz), but over 35% of the links have zero mutual information. The NBS, on the other hand, gives a reasonably fair distribution: the mean mutual information is slightly lower (5.98 bits/sec/Hz), but individual link quality is maintained much more effectively.



**Figure 29: Normalized error bounds versus time at the channel center frequency.**

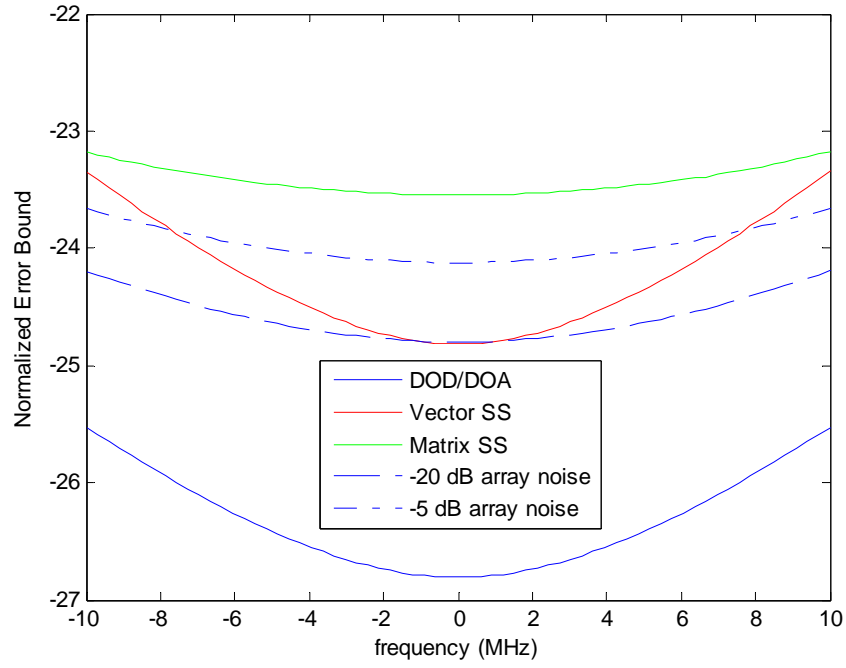


Figure 30: Normalized error bounds versus frequency for a fixed moment in time.

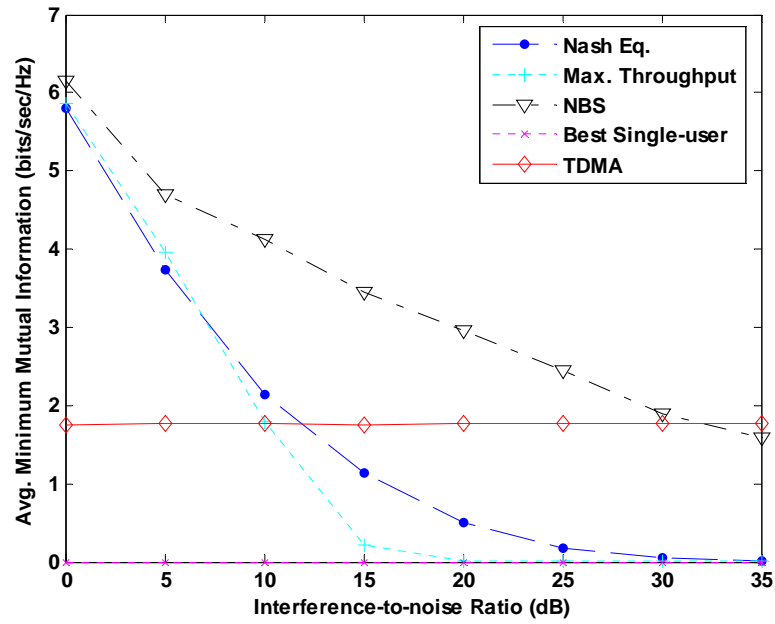


Figure 31: Minimum Mutual Information as a function of INR for various power allocation strategies.

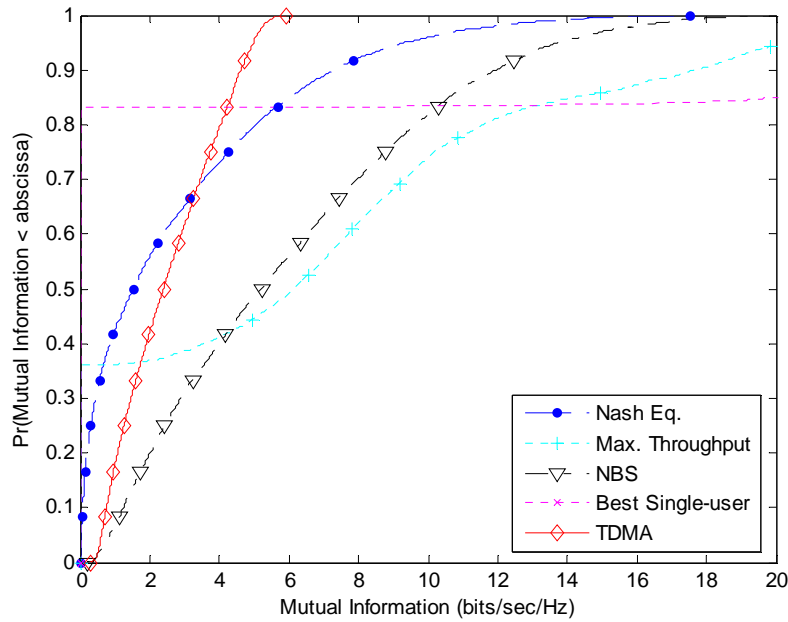


Figure 32: CCDF of Mutual Information for various power allocation strategies.

## 6.12 MIMO Channel Equalization and Multiple Access Suppression at the Transmitter

PI: John Proakis

GSR: Patrick Amihoud

### Previous Work and Background

In MIMO ad-hoc networks, it is desirable to simplify receiver design so as to minimize power consumption. For example, the receiver may not jointly process the signals received on the multiple antennas. Therefore, the burden may fall on the transmitter to spatially equalize the channel. Moreover, in the presence of frequency selective fading, the transmitter must also perform temporal equalization. Precoding at the transmitter can unburden the receiver by performing joint spatial and temporal equalization. This technique is also employed in multiuser MIMO systems, where the receivers are not co-located and, consequently, may not jointly process the signals received at different receivers.

The focus of our work has been on signal design and equalization for MIMO ad-hoc networks [1]. Suppose two communicating nodes can come to an agreement on whether the transmitter or the receiver will perform equalization, based on the power availability of each node. While equalization at the receiver has been studied extensively, we have provided analytical results on a specific precoding scheme that performs equalization at the transmitter [2],[3]. These results have allowed further analytical investigation into the tradeoffs associated with equalizing at the transmitter or the receiver under more realistic assumptions such as imperfect channel estimation [4]. In the next section we give an overview of our work on precoding with imperfect channel

estimation. Here, we begin with a brief background on our initial work on precoding when the channel is known.

The precoding scheme that we have investigated is based on the QR decomposition of the channel matrix. The channel matrix is known perfectly at the transmitter and is a realization of a matrix whose entries are i.i.d. complex Gaussian random variables. The QR decomposition enables us to express the equivalent channel as an upper-right triangular matrix, thus enabling Successive Interference Cancellation (SIC). While equalization at the receiver can cause noise enhancement, equalization at the transmitter can cause the required transmit power to vary over a large range. This is due to the SIC, which feeds back the spatial and temporal interference. We employ Tomlinson-Harashima precoding to limit the transmit power. This is accomplished by a modulo operation at both the transmitter and the receiver. The signal is then transmitted over a frequency selective fading channel to a receiver with multiple antennas. As a result of precoding, the signals at each receive antenna see no interference due to the signals intended to the other antennas or due to the ISI.

We have obtained an expression for the conditional probability of symbol error as a function of the average SNR-per-bit, the number of transmit and receive antennas, the number of paths between each antenna pair, and the parameter indicating the size of the square M-QAM constellation. This expression includes the effect of Tomlinson-Harashima precoding, which causes a slight degradation in performance due to the modulo operations. The effect of Tomlinson-Harashima precoding is negligible at high SNR, since the thermal noise component of the test statistic is less likely to effect the modulo operation.

To obtain the unconditional probability of symbol error, we averaged over the distribution of the squared-diagonal elements of the upper-right triangular matrix associated with the QR decomposition of the channel matrix. It is shown that these squared-diagonal elements are independent scaled chi-squared distributed random variables with different degrees of freedom.

We investigated the effect of the optimal ordering of the receive antennas. Each ordering is associated with a different QR decomposition and each decomposition requires a different transmit power. While it is possible, for a given channel matrix, to search over all possible permutations to obtain the ordering that minimizes the transmit power, and while algorithms exist that simplify this search, we approached the problem analytically, deriving the distribution of the squared-diagonal elements of the upper-right triangular matrix associated with the *optimal* QR decomposition of the channel matrix.

The key to deriving the required distribution associated with the optimal ordering, is to express the squared-diagonal elements of the QR decomposition in terms of the inner-products of the columns of the channel matrix. The inner-products are shown to be Wishart distributed. The required distribution associated with the optimal ordering reduces to an integration of the Wishart density over a complicated region. Since it is difficult to express the limits of integration explicitly, we found a closed-form expression for the probability density function of the squared-diagonal elements of the upper-right triangular matrix belonging to the optimal QR decomposition when two transmit antennas and two receive antennas are employed.



Simulations corroborated the analytical results, both for an unordered and the ordered QR decomposition. It was shown that an increase in the number of transmit antennas increases the spatial diversity available in the system. This can be explained by observing that the probability of symbol error is a function of the squared-diagonal elements of the upper-triangular matrix. Their degrees of freedom increase for an increasing number of transmit antennas. It was also shown that minimizing the total transmit energy by selecting the optimal order results in improved performance compared to an unordered QR decomposition.

## Summary of Achievements

The main contribution of our recent work [4] includes an analysis of the effects of channel estimation errors on the performance of a system employing Tomlinson-Harashima precoding and the QR decomposition for MISO channels with decentralized receivers operating over frequency-flat fading channels. As in our previous work [2], [3], we use the QR decomposition technique to enable successive interference cancellation. Due to imperfect channel estimation which causes a mismatch between the precoder and the channel, multiuser interference is present at the receivers and must be accounted for in the derivation of the probability of symbol error. In addition, as in the case when the channel is known, performance is degraded by the increase in power inherent in the precoding technique.

The system considered in [4] is the same as the pre-BLAST-DFE technique that is presented in [2], [3], except for the fact that we do not consider ordering of the decentralized receivers.

The model for channel estimation used in this work is the same as the model used in [5]. In the uplink transmission, geographically separated users transmit training sequences which are used by the receiver with co-located antennas to estimate the channel. Assuming time division duplex (TDD) and a large enough channel coherence time such that the channel does not change significantly between uplink and downlink modes, the channel estimates formed in the uplink transmission can be employed in the downlink.

The work in [5] attempts to derive the probability of symbol error for the same system considered in our work, except that, in [5], the number of transmit antennas is equal to the number of receive antennas whereas, in our work, we also consider the case when the number of transmit antennas is greater than the number of receive antennas. In [5], matrix differentials are applied to derive the precoding matrices, which are formed from realizations of the channel by assuming the channel estimation error,  $\mathbf{MH}$ , is small. Indeed, the entries of  $\mathbf{MH}$  are normally distributed and, in this paper, we show that the entries are i.i.d. with variance proportional to  $1/N_{\text{Tr}}$ , where  $N_{\text{Tr}}$  is the length of the training vectors used for channel estimation. For large enough  $N_{\text{Tr}}$ , which is a design parameter, the variance of the entries of  $\mathbf{MH}$  can be made small. However, there is no guarantee that actual realizations of the entries of  $\mathbf{MH}$  are small, and therefore, it is unclear whether the analysis in [5] can be rigorously justified.

Furthermore, there are several errors in the analysis in [5] associated with Lemma 1. This Lemma is used in [5] to show that the contribution of the channel estimation error  $\mathbf{MH}$  to the test statistic is asymptotically Gaussian. Unfortunately, Lemma 1 is a misquotation of Theorem 3.3A in [6]: This latter theorem, which deals with nonlinear transformations of asymptotically

Gaussian random vectors, requires that 1) the differential of the transformation is nonzero, 2) the value of this differential must be computed explicitly in order to obtain the asymptotic variance/covariance matrix of the transformed variables. There is no evidence that these two steps have been carried out in [5]. Moreover, we have carried out the analysis in [5] for the special case of one transmit and one receive antenna using Lemma 2 (perturbation approximation) of [5]: It turned out the value of the differential (first order partial derivative evaluated at the origin) is actually equal to zero and therefore Theorem 3.3A of [6] is not applicable. Thus, Lemma 1 of [5] cannot be used to deduce that the contribution of the channel estimation error to the test statistic is asymptotically Gaussian. This counter example shows that the analysis of [5] is unfortunately erroneous.

We arrive at our results by different techniques, effectively avoiding having to establish the dependencies of various random variables by initially deriving the conditional probability of symbol error, conditioned on the elements of the actual channel matrix as well as the elements of the channel estimation error matrix. The conditional probability of symbol error is then averaged by integration over the densities of these random variables, leading to results that coincide with simulations.

Both [7] and [8] consider receiver equalization with the QR decomposition approach, and both use the same channel estimation model employed in this paper. The outage probability due to channel estimation is computed in [7] by approximating one of the matrices derived from the QR decomposition of the imperfect channel estimation matrix by one of the matrices derived from the QR decomposition of the actual channel matrix. This is convenient, since the actual channel matrix is independent of the error estimation matrix. The same approximation is made in [8]. Furthermore, in deriving the probability of symbol error, the dependency between the channel estimation matrix and its QR decomposition is implicitly ignored in [8]. Our approach does not make any of these approximations.

After obtaining an expression for the unconditional probability of symbol error, it is evaluated by numerical integration using the variance reducing technique of importance sampling. Since the region of integration is large, and the integrand is small over most of the multidimensional space, then approximating the distribution and sampling accordingly gives more accurate results for a given number of samples than does blind sampling.

Figure 33 illustrates the probability of symbol error as a function of the SNR-per-bit with  $M=4$  (QPSK), the number of transmit antennas  $N_T=2$ , the number of users  $N_U=2$ , and the variance of the channel estimation error  $\sigma_e^2=0, 0.001, 0.01$ , and  $0.1$ . The analytical results obtained by numerical integration coincide with the simulation results. The simulation results are obtained by averaging the probability of symbol error over 100,000 realizations of the channel. As  $\sigma_e^2$  increases, performance degrades significantly compared to the case when the channel is known ( $\sigma_e^2=0$ ).

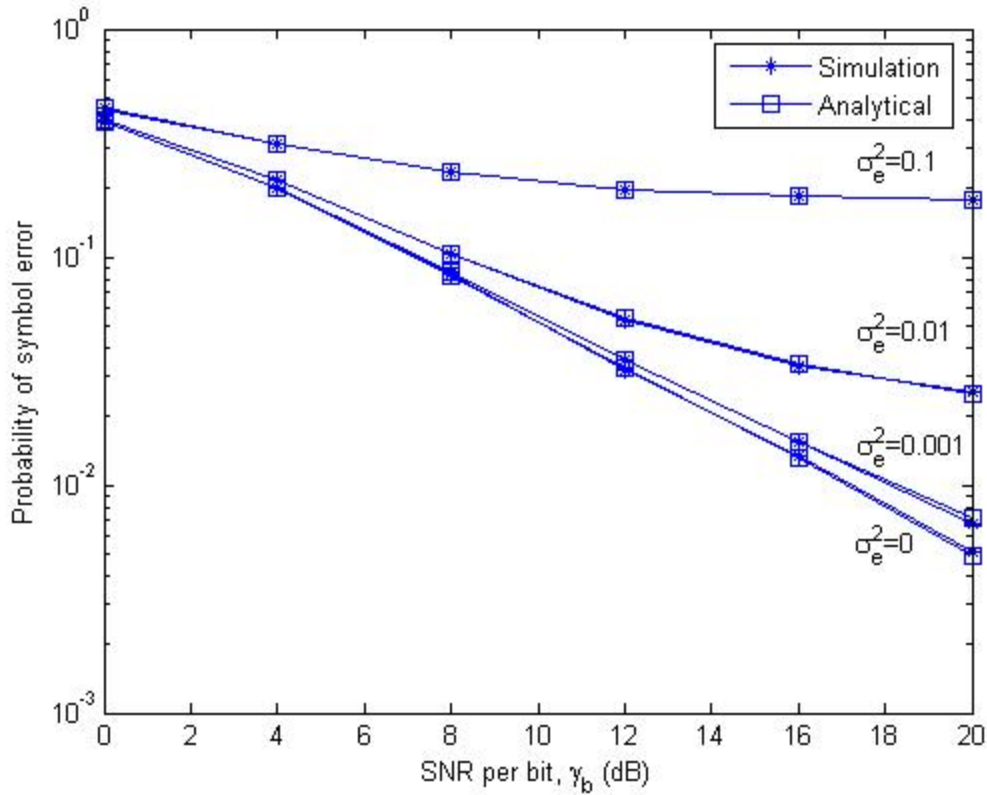


Figure 33: The probability of symbol error as a function of the SNR-per-bit for Tomlinson-Harashima precoding and the QR decomposition technique operating over a MISO frequency-flat fading channel with decentralized receivers. The results are obtained by numerical integration and by simulations. Here,  $N_T=N_U=2$  and  $\sigma_e^2=0, 0.001, 0.01$ , and  $0.1$ .

## Future Work

An immediate extension our work includes a comprehensive analysis and comparison of linear and nonlinear precoders, with and without channel estimation. Furthermore, it is important to understand the performance of precoding compared to equalizing at the receiver. Whether it is advantageous for the transmitter to perform equalization as opposed to the receiver is a question that can be posed by considering the costs associated with the receiver feeding back an estimate of the channel to the transmitter. On the other hand, the benefits of equalizing at the receiver can be considered in light of the costs associated with using imperfectly detected symbols in order to perform successive interference cancellation.

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### **6.13 Stable Transmission in the Multi-User, Time-Varying, MIMO Broadcast Channel**

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**GSR: Adam Anderson**

In previous years we have shown the use of channel distribution information (CDI) in order to provide stable signal gains in the single-user MIMO channel. Specifically, the form of CDI used consists of transmit and receive spatial correlation matrices upon which beamforming weights are derived. Due to the high temporal variability of the dominant eigenvectors of the channel matrix, beamforming using channel state information (CSI) has initially high throughput, but then quickly degrades as channel subspaces change. Beamforming using CDI provides a suboptimal yet stable subspace upon which signal channel gains remain constant over longer periods of time. The differing time-scales between CSI and CDI beamforming are important quantities to which protocol designers may adapt.

The focus of work for this year was in extending the single-user results from previous years to include the multi-user, MIMO channel. This extension is beneficial to the ultimate goal of ad hoc network protocol design in that it provides both stable transmission in the time-varying channel *and* multiple access to the wireless medium. Thus this analysis approaches the complexity of even larger ad hoc networks and provides insight into cross-layer precoding techniques. The results of the preceding year will provide cross-layer designers further insight into what

information is possible and available at the various network layers and the time-scale at which such information should be used. The major accomplishments are enumerated as follows:

- 1) *Capacity analysis of the multi-user (modeled [4] and measured [2]) channel when channel state information at the transmitter is outdated or erroneous.* This analysis provides expressions for mutual information for three different types of transmit precoding: dirty-paper coding (DPC), linear beamforming (BF), and uninformed time-sharing (UTS). These expressions are derived focusing on the time-variation in the channel and are a function of the lag between channel updates and channel knowledge use.
- 2) *We present a novel beamforming technique that uses no CSI at the transmitter and is able to produce stable throughput in the channel.* This beamforming algorithm is performed by maximizing the average rather than instantaneous mutual information. It is further shown minimum displacements required in order for CDI beamforming to outperform transmission schemes that use CSI. Such stable transmissions are ideal for higher layer protocols that require a certain amount of available delay between decision and action.

## 1. Multi-User, Time-Varying MIMO Broadcast Channel Analysis

An important decision made by any system is the type of transmit precoding to be used given some knowledge of the channel and environment. Choosing a specific precoding technique can provide significant gains over blind transmission while the wrong precoder will result in severe performance degradation. Specifically, we have examined three different types of precoders: nonlinear, linear, and blind, each of which provide insight into the time-scale variations of the channel.

### A. Dirty-Paper Coding

Dirty-paper coding (DPC) is a nonlinear transmit precoding algorithm that pre-subtracts known multi-user interference at the transmitter [1]. DPC requires highly accurate CSI at the transmitter and receiver in order to provide the theoretical optimal gains. The mutual information (MI) of a system using DPC given some estimate of the current channel can be written as

$$I_{DPC}[\mathbf{x}_j(n); \mathbf{y}_j(n_0, n) | \mathbf{H}_j(n), \mathbf{H}_j(n_0)] = \log \frac{|\mathbf{Z}_i + \mathbf{H}_i(n) \mathbf{Q}_i \mathbf{H}_i^\dagger(n)|}{|\mathbf{Z}_i|}$$

$$\mathbf{Z}_i = \mathbf{I} + \sum_{j=i+1}^K \Psi_{i,j}^{\mathbf{H}(n)} + \sum_{j=1}^{i-1} \Psi_{i,j}^{\mathbf{E}(n_0, n)}$$

where MI is a function of the channel estimate at sample  $n_0$  and the current channel at sample  $n$ . Notice that in addition to the standard MI expression from [1], DPC with outdated CSI causes additional errors for each successively encoded user. This added error term suggests a more significant performance loss than other transmit precoders.

### B. Linear Transmit Beamforming

Beamforming (BF) is a linear transmission method that attempts to mitigate interference and maximize received signal power by finding appropriate subspaces of the current channel matrix. Given a set of transmit beamforming weights with input covariance  $\mathbf{Q}_i$  the mutual information for user  $j$  can be written as

$$I_{BF}(\mathbf{x}_j(n); \mathbf{y}_j(n_0, n) | \mathbf{H}_j(n), \mathbf{H}_j(n_0)) = \log \frac{|\mathbf{I} + \mathbf{H}_j(n) (\sum_{i=1}^K \mathbf{Q}_i) \mathbf{H}_j^\dagger(n)|}{|\mathbf{I} + \mathbf{H}_j(n) (\sum_{i \neq j}^K \mathbf{Q}_i) \mathbf{H}_j^\dagger(n)|}$$

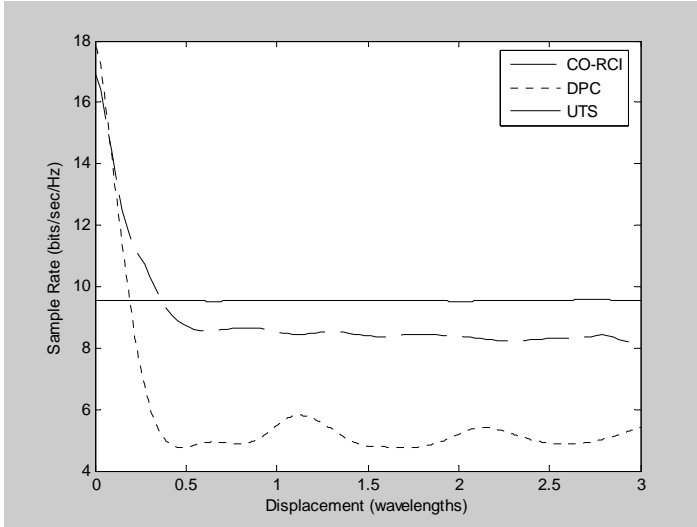
Note that the only degradation seen using BF is caused by outdated BF weights. This is in contrast to DPC which has outdated  $\mathbf{Q}_i$  and self-interference terms. This observation implies that DPC will suffer more from outdated CSI than BF. The beamformer that optimizes capacity uses a regularized channel inversion and will be referred to as CO-RCI.

### C. Uninformed Time-Sharing

Uniformed time-sharing (UTS) is a straightforward method of removing performance loss of outdated CSI at the expense of initial suboptimality. UTS uses no CSI at the transmitter and assumes some form of scheduling was used to give each data stream exclusive access to the channel at a specific time instance. Under this precoding scheme, and for  $K$  users, MI is written as

$$I_{UTS}(\mathbf{x}_j(n); \mathbf{y}_j(n) | \mathbf{H}_j(n)) = \frac{1}{K} \log \left| \mathbf{I} + \frac{P}{N_t} \mathbf{H}_j(n) \mathbf{H}_j^\dagger(n) \right|$$

Note that this expression is only a function of the current channel and is independent of channel updates or lag.



**Figure 34: Loss in expected sample rate versus displacement between channel update and use. This simulation represents a broadcast channel with five users each equipped with four antennas and a transmitting node also with four antennas. The measured channel data was used.**

Given expressions for mutual information for each of the transmit precoders under consideration it is straightforward to examine performance loss for any channel type including both measured and modeled channels. Figure 34 displays the loss in MI when using the various types of transmit precoders with outdated CSI. The channel realizations were taken from a dataset created

by the Brigham Young University (BYU) measurement equipment in an outdoor urban environment [2]. Figure 34 demonstrates the significant loss in performance when using DPC or BF and the stability, though initial suboptimality, of UTS.

## 2. Stable Beamforming in the MIMO Broadcast Channel

Careful consideration of the results demonstrated in the previous section suggests a method of describing transmit precoding that is more stable against temporal variations in the channel and provides higher throughput.

- 1) *Nonlinear transmission is the most sensitive to outdated CSI.* The self-interference caused when using DPC suggests that a linear beamforming will provide better stability results.
- 2) *At large displacements the best precoder uses no CSI.* The loss in performance from Figure 34 is exclusively from outdated CSI in the time-varying channel. A stable transmit precoder needs to be based on something other than CSI.
- 3) *The most stable transmission scheme maximizes average MI rather than instantaneous MI.* Rather than attempting to maximize the capacity (as DPC and BF do), a scheme that maximizes *ergodic* capacity may result in more stable performance.

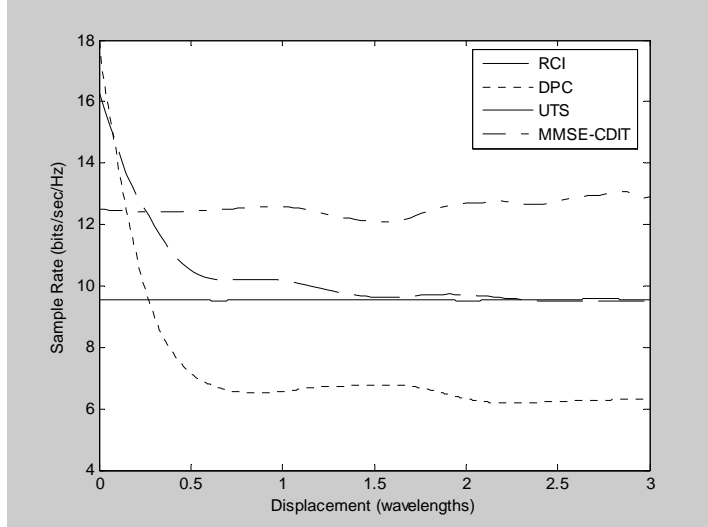
In order to find an algorithm that provides both stable performance and increased throughput over the UTS scheme, each of the above observations was used. A lower bound on average mutual information was found which results in a function based solely on the spatial transmit correlation matrices  $\mathbf{R}$  rather than individual channel samples. Using this as an objective function, the coordinated transmit/receive beamforming algorithm from [3] was used for optimization purposes. Table 2 is an outline of the given algorithm when used on CDI beamforming (called MMSE-CDIT). An interesting result of the CDI beamformer is that it results in optimal instantaneous performance when CSI is used instead of CDI.

**Table 2: Beamforming Algorithm for Maximization of Average Expected Throughput.**

<ol style="list-style-type: none"> <li>1. Assume an initial set of <math>N_s</math> random transmit weights <math>\mathbf{b}_i</math></li> <li>2. Calculate the MMSE <i>receiver</i> weights for all streams to all users  <math display="block">\mathbf{w}_{i,j} = (I + \mathbf{R}_j (\sum_{k \neq i} p_k \mathbf{b}_k \mathbf{b}_k^\dagger) \mathbf{R}_j^\dagger)^{-1} \mathbf{R}_j \mathbf{b}_i p_i</math></li> <li>3. Find the survivor streams by using  <math display="block">\pi(i) = \arg \max_j \tilde{p}_{i,j}</math></li> <li>4. Update the MMSE <i>transmitter</i> beamforming weights  <math display="block">\mathbf{b}_i = (I + \mathbf{R}_{\pi(i)}^\dagger \sum_{k \neq i} p_{\pi(k)} \mathbf{w}_{\pi(k)} \mathbf{w}_{\pi(k)}^\dagger \mathbf{R}_{\pi(i)})^{-1} \mathbf{R}_{\pi(i)} \mathbf{b}_{\pi(i)} p_{\pi(i)}</math></li> <li>5. Repeat 2-4 until convergence</li> <li>6. Repeat 1-5 for <math>N_s = 1 \dots K</math></li> <li>7. Use <math>\mathbf{w}_{i,\pi(i)}</math> corresponding to the value of <math>N_s</math> that maximizes  <math display="block">C_{\text{MMSE-CDIT}} = \sum_{i=1}^{N_s} \log(1 + \tilde{p}_{i,\pi(i)})</math></li> </ol>
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Using the suggested MMSE-CDIT beamformer, the same simulations can be run as performed on the other transmit precoders in Figure 34. Figure 35 shows these same results as Figure 35 but with the addition of the MMSE-CDIT beamforming algorithm. The observations used to motivate the steps of this algorithm are validated in the results in Figure 35. MMSE-CDIT

beamforming maximizes the average throughput versus all other transmit precoding schemes. Additionally, it outperforms UTS by including knowledge of the distribution of the channel at the transmitter. An interesting result of MMSE-CDIT beamforming is that even without any knowledge of the channel at the transmitter, multiple access to the channel is still optimal. In other words, the output of the MMSE-CDIT beamforming algorithm always has more than one non-zero weight vector. This implies that network optimizers can gain significant throughput while maintaining stable performance by using CDI rather than CSI at link ends.



**Figure 35: Loss in expected sample rate versus displacement between channel update and use. Included is the transmit beamformer using CDI. The simulation used is the same as in Figure 1 though with a different dataset.**

### 3. Summary

The results presented this past year are promising in providing network protocol designers with information necessary to optimize the network throughput. Stable channel gains are possible by a beamforming scheme that uses the channel distribution (CDI) rather than realization (CSI) in order to find slowly varying subspaces. This beamforming algorithm attempts to maximize the average MI in order to mitigate the variation in performance curves. Adaptive policies between CSI and CDI are possible depending on quality guarantees and necessary delays of the channel and network overhead. Such adaptation will be a necessary part of any protocol that hopes to optimize network efficiency.

Extensions of this work are straightforward and will provide further insight and tools for the network designer:

- 1) *CDIR beamforming in the broadcast channel.* For extremely high mobility or delay, it may be impossible to achieve accurate CSI at the receiver (CSIR). In this scenario the performance of CDIR beamforming would help alleviate the loss in performance when using outdated CSIR.
- 2) *CDIT/R beamforming in the multiple-access channel.* The dual of the broadcast channel is the multiple-access channel and can also be used extensively in ad hoc networks. The performance of CDI beamforming for these channels is not fully explored and includes the extra difficulty of separating multiple data streams at the receiver without any CSI.



- 3) *CDI as an ad hoc network resource.* How an ad hoc network MAC/ Routing protocol would efficiently use both CSI and CDI has not been thoroughly explored yet in the literature. The loss in performance of outdated CSI and stability of CDI can both be significant and will be explored.

These research topics will be addressed in the coming year in the context of improving cross-layer efforts of the network protocol stack.

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## 6.14 Antennas and Propagation for Space-Time Communications in Mobile Ad Hoc Networks

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**GSRs:** Chan Chen, Britton Quist

**Post-Doc:** Haroon Stephen

### SUMMARY OF ACCOMPLISHMENTS

During this period we have primarily emphasized two research projects relevant to the overall focus of antenna design and channel characterization for MIMO communications in mobile ad hoc networks:

1. *Modeling of the Time-Variant MIMO Channel:* Our previous research has revealed the dramatic impact of outdated channel state information (CSI) on the performance of MIMO systems, both for point-to-point and multi-user scenarios. However, to fully explore the implications for real systems and to allow efficient evaluation of new physical and higher layer methods for implementing space-time communications for mobile nodes, channel models capable of capturing the time evolution are necessary. We have developed such models, and are currently refining them to even more accurately capture the channel physics.
2. *Optimal Antenna Design:* A common request from industry is help in identifying good antenna designs for use in MIMO communication. However, the current state-of-the-art lacks design principles and definitions of optimality, and therefore design is based on rule-of-thumb suggestions. We have been able to define a method for determining the

optimal antenna characteristics given a very general stochastic description of the propagation environment of operation. This work includes evaluating the impact of imperfect terminations for compact arrays used on portable devices.

In the following sections, we summarize our progress in these areas.

## **Modeling the Time-Variant MIMO Channel**

Our goal is to explore the extension of conventional MIMO channel modeling techniques to time-varying channels by extracting model parameters from measured data and using information theoretic metrics to determine if the models capture the correct channel behavior. Although many models exist, we focus on (1) a random matrix model following the multivariate complex normal (MVCN) distribution and (2) a physical time-variant clustering (TVC) model. The MVCN model parameters can be directly estimated from collected data, but can be difficult to interpret physically. In contrast, the TVC model exhibits a compelling physical interpretation, although unique extraction of cluster parameters can be difficult.

### ***MVCN Model***

We represent the complex gain from the  $j$ th transmitter to the  $i$ th receiver at time index  $n$  for a single frequency bin as  $H_{ij}^{(n)}$ . If these gains follow a (possibly time-dependent) MVCN distribution in both time and space, the spatio-temporal variation of the MIMO channel is completely characterized by the multivariate mean and covariance. For a stationary distribution, the mean and variance are not a function of  $n$  and can be obtained with sample averages. The difficulty of extracting these parameters from a non-stationary process depends on the severity of the non-stationarity, and may even be impossible for overspread processes. Here, we consider a process characterized by a mean and covariance that vary slowly in time, allowing estimation by weighted (windowed) sample averages. In this work, we apply an exponential window whose size is based on the correlation length.

Determining the distance over which the channel can be considered a stationary process is non-trivial. One option is application of direct statistical tests for multivariate normality applied to the channel data stacked into a vector. If either the data is non-normal or moments are time-variant, the tests should fail. Thus, the window size can be determined by increasing the size of the data window until these statistical tests begin to indicate non-conformance.

Because no single test is robust against all possible alternative distributions, several tests should be applied to assess normality. We determine a suitable value for the window size by applying three different tests for multivariate normality: (1) Mardia's tests for multivariate skewness and (2) kurtosis [1], and (3) the Henze-Zirkler test [2] with  $\alpha = 0.5$ . Application of these tests reveals acceptable rejection rates for distances of 4-8 wavelengths for indoor data and 8-16 wavelengths for outdoor data.

### ***Synthetic Channel Generation***

Once the time-varying mean and covariance have been estimated from the data via, we require a way of generating simulated channels. There are a variety of methods for accomplishing this. Perhaps the simplest approach is to assume that the covariance is separable in the time and space,

with values for the separate space and time covariances obtained by averaging the full covariance over all time steps and antennas, respectively. The synthetic channels are then generated stepwise as

$$B_{ij}^{(n)} = \sum_{n'} X_{T,nn'} A_{ij}^{(n')}$$

$$H_{ij}^{(n)} = \sum_{i'j'} X_{S,ij,i'j'} B_{i'j'}^{(n)}$$

where  $\mathbf{X}_T = \mathbf{R}_T^{1/2}$ ,  $\mathbf{X}_S = \mathbf{R}_S^{(n)1/2}$ ,  $R'_{T,nn'} = R_T^{(n,n'-n)}$ ,  $i$  and  $j$  are stacked when used as a covariance index, and  $A_{ij}^{(n)}$  are i.i.d. complex normal random variables.

To reduce the number of model parameters, an average value for the temporal correlation is used at each time step. We refer to this model with a coherent average of the temporal correlations as MVCN(CE) where CE stands for complex envelope. On the other hand, the averaging can be performed incoherently, and this is referred to as MVCN(PE) for power envelope. Forcing this space-time separability and averaging the temporal correlation reduce the accuracy of the MVCN model. However, such simplifications seem necessary to arrive at a model which is reasonable in terms of both computational burden and parametric complexity.

### ***TVC Model***

The double-directional channel concept is a powerful technique for system-independent representation of spatial channels, and much research effort has been dedicated to extracting the parameters for individual multipath components from measured data. Alternatively, we can treat the channel as an incoherent process described by a double-directional power spectrum [3]. This method groups multipath components into clusters of arrivals and departures and estimates only the cluster parameters.

### ***Cluster Extraction***

The first step is to define the clusters in a measured channel. This is accomplished by the following steps:

1. The average Bartlett spectrum is computed for all time steps in a data record.
2. A set of clusters is estimated from the average Bartlett spectrum, and the dominant clusters, representing 90\% of the channel power, are retained.
3. The time-variant Bartlett spectrum is computed for each time step.
4. Using linear programming, best-fit values for the cluster amplitudes are estimated at each time step for the reduced set of clusters found in step 2.

Since the full joint double-directional estimation problem results in a very large coefficient matrix, we simplify the method by first estimating one-dimensional clusters for single-directional transmit and receive to determine which basis functions are significant. Then, only the significant clusters are used in the joint two-dimensional estimation.

### ***Synthetic Channel Generation***

Synthetic channels are generated by assuming  $L$  rays per cluster and computing the channel response as

$$H_{ij}^{(n)} = \frac{1}{\sqrt{L}} \sum_{p,\ell} a_p^{(n)1/2} \beta_{p\ell} \psi_{R,p\ell}(\phi_{R,p\ell}) \psi_{T,p\ell}(\phi_{T,p\ell})$$

where the different variables are specified by the cluster extraction. Extensions to the model include allowing a different number of rays (richness) in each cluster, rays that dynamically appear or disappear in time, a time-variant set of clusters, etc. For this work, a fixed set of  $L=50$  rays per cluster is assumed for each realization of the model. Also, note that this current model only attempts to fit the channel covariance, and has no provision for including non-fading components (channel mean).

### Model Comparisons

We now compare the results of applying the capacity degradation metrics [3] to the models and measured data. We show only the results for indoor data at 2.55 GHz, since all other results lead to similar conclusions.

Figure 36 plots the fractional RMS error in the RCD metric as a function of distance for indoor data for three different models. The discrepancy between the MVCN(CE) and MVCN(PE) results may stem from the fact that the coherent averaging will tend to underestimate the temporal correlation if the process is not stationary over the entire data window. Figure 37 plots the fractional RMS error of the TCD metric for the same set of data. In this case, the MVCN(PE) and MVCN(CE) models give nearly identical results, so only the results for MVCN(PE) are plotted.

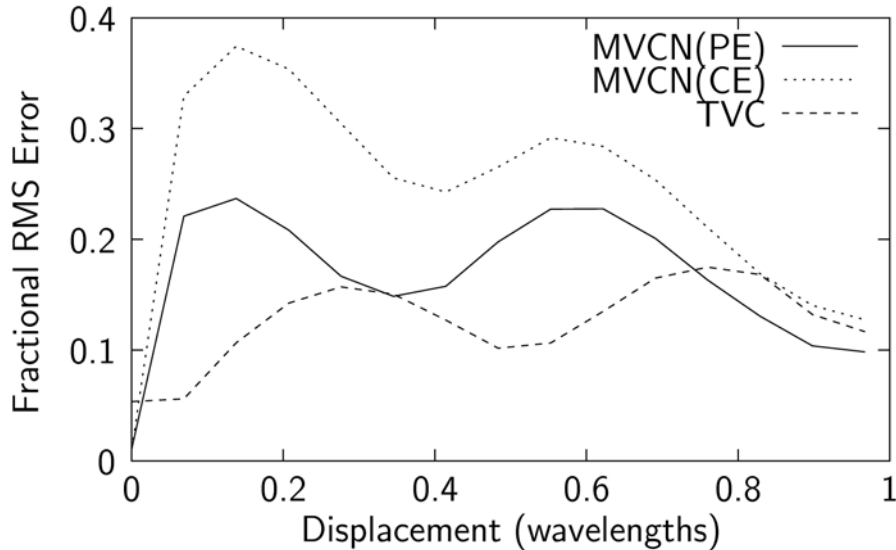


Figure 36: RMS error in the RCD capacity metric for the TVC model and MVCN model with power envelope (PE) and complex envelope (CE) temporal correlation.

These results suggest that the MVCN model works well for long-term channel variations. This is intuitive, since at large displacements the temporal statistics are independent and only the spatial covariance, which is properly represented at each time step, impacts the results. The failure of the model to adequately match the metrics for short displacements implies that the separable time-space assumption is rather poor. The good performance of the TVC model is somewhat

remarkable, considering we only consider a small set of clusters and generate a fixed set of 50 rays for each cluster. This accuracy suggests that the random combination of a constant set of rays properly captures the short-term spatio-temporal covariance.

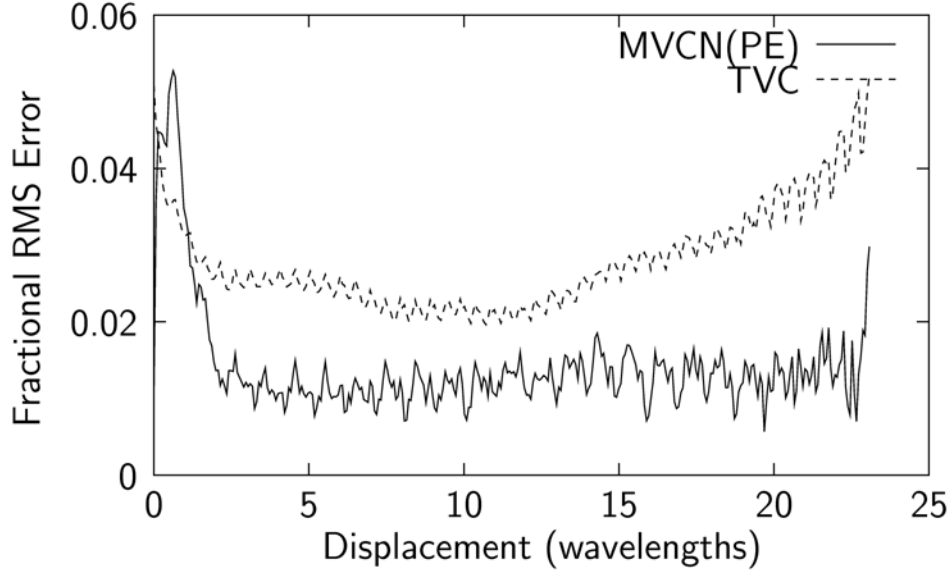


Figure 37: RMS error in the TCD capacity metric for the TVC model and MVCN model with power envelope (PE) temporal correlation}

## Optimal Antenna Design for Mobile MIMO Nodes

It has been well-established that good diversity or multiple-input multiple-output (MIMO) performance requires the use of antennas whose patterns (phase, magnitude, and or polarization) are nearly orthogonal [4]. While this general observation is helpful when considering the design of multi-antenna systems, effective antenna synthesis requires a more explicit mathematical formulation of the optimal antenna radiation patterns for a given scenario. The goal of this paper is to provide such a formulation, taking into account issues such as limited antenna aperture and limits on allowable array superdirectivity. Computational results demonstrate implementation of the approach and quantify the performance achieved with the radiation from practical geometries relative to that of the optimal radiation patterns.

### *Formulation*

Because MIMO systems use multiple antennas at both the transmitter and receiver, full system characterization requires analyzing the entire link. However, effective antenna design strategy should be possible when considering the transmitter and receiver separately. Since both MIMO and diversity systems operate on the principle of exploiting the spatial degrees of freedom enabled by the antennas and propagation environment, antennas designed for good diversity performance will also yield good MIMO performance. We will therefore characterize antennas based on diversity considerations.

Consider a scenario in which the receiver channel power angular spectrum (average power per unit angle) is given by  $\overline{\overline{\mathbf{P}}}(\Omega)$ , where the double-overbar indicates a polarization tensor and  $\Omega$  is

the solid angle. If  $\bar{\mathbf{e}}_m(\Omega)$  represents the open-circuit radiation pattern of the  $m$ th receive antenna, the incident field is a zero-mean Gaussian random process, and the field arriving at one angle is uncorrelated with that arriving at another angle, the covariance for the open-circuit voltages on the antenna terminals is given by [4]

$$R_{mp} = \varphi^2 \int_{\Omega} \bar{\mathbf{e}}_m(\Omega) \cdot \bar{\mathbf{P}}(\Omega) \cdot \bar{\mathbf{e}}_p^*(\Omega) d\Omega$$

where  $\varphi$  is a constant.

An optimal set of antennas for maximizing diversity performance should generate a covariance matrix which satisfies two criteria:

1. Diagonal elements large, indicating that each antenna element receives a large amount of signal power.
2. Off-diagonal elements zero, indicating that the radiation patterns are orthogonal with respect to the power angular spectrum of the incident field.

The goal is to design the optimal set of antennas which accomplishes these goals, taking into account the aperture in which the antennas reside.

Although we are considering the antenna operating in reception, it is intuitive to define the radiation patterns in terms of radiating currents. Consider a volume  $V$  containing a set of vector electric current functions  $\bar{\mathbf{j}}_m(\bar{\mathbf{r}})$  each having a radiation pattern given by

$$\bar{\mathbf{e}}_m(\Omega) = \int_V \bar{\mathbf{G}}(\Omega, \bar{\mathbf{r}}) \cdot \bar{\mathbf{j}}_m(\bar{\mathbf{r}}) d\bar{\mathbf{r}}$$

where  $\bar{\mathbf{G}}(\Omega, \bar{\mathbf{r}})$  is the dyadic Green's function relating the currents to the far-field radiation. We represent each current function as a weighted sum of vector basis functions  $\bar{\mathbf{f}}_n(\bar{\mathbf{r}})$ , or

$$\bar{\mathbf{j}}_m(\bar{\mathbf{r}}) = \sum_n B_{nm} \bar{\mathbf{f}}_n(\bar{\mathbf{r}})$$

where  $B_{nm}$  represents a weighting coefficient. Use of this expansion yields  $\mathbf{R} = \mathbf{B}^T \mathbf{C} \mathbf{B}^*$ , where

$$C_{nq} = \int_{\Omega} \bar{\mathbf{z}}_n(\Omega) \cdot \bar{\mathbf{P}}(\Omega) \cdot \bar{\mathbf{z}}_q^*(\Omega) d\Omega$$

and  $\bar{\mathbf{z}}_n(\Omega)$  represents the radiation pattern due to the  $n$ th basis function.

We enforce a constraint to ensure each antenna pattern has the same radiated power, and use an eigen-analysis to determine the optimal coefficients  $B_{nm}$ . We include a loss resistance into the formulation to ensure that superdirective antennas are not incorporated.

### Example Computation

We restrict ourselves to a two-dimensional scalar scenario where the incident field and the antenna aperture lie in the horizontal plane. The signal power angular spectrum is defined by a truncated Laplacian distribution. Assuming a square aperture of side length  $L$  in which the currents reside, the basis functions used for the computation are Fourier functions defined by

$$f_n(\Omega) = \exp[j(k_{xn}x + k_{yn}y)]$$

where  $k_{xn} = 2\pi r / L$ ,  $k_{yn} = 2\pi s / L$ ,  $n = (s+S)(2R+1) + (r+R)$  for  $-R \leq r \leq R$ ,  $-S \leq s \leq S$ . We will assume  $L$  is one wavelength and  $R = S = 5$  (121 basis functions).

Figs. 38 and 39 show the four best current distributions and the resulting radiation patterns for this scenario when the loss is chosen such that the radiation efficiency for the basis function with the largest radiation resistance is 99%. For comparison, an array of four Hertzian dipoles placed at the corners of the aperture are also simulated. In this case, the optimal antennas provide 4.7 dB more diversity gain than the array of dipoles (at the 1 % probability level) [4].

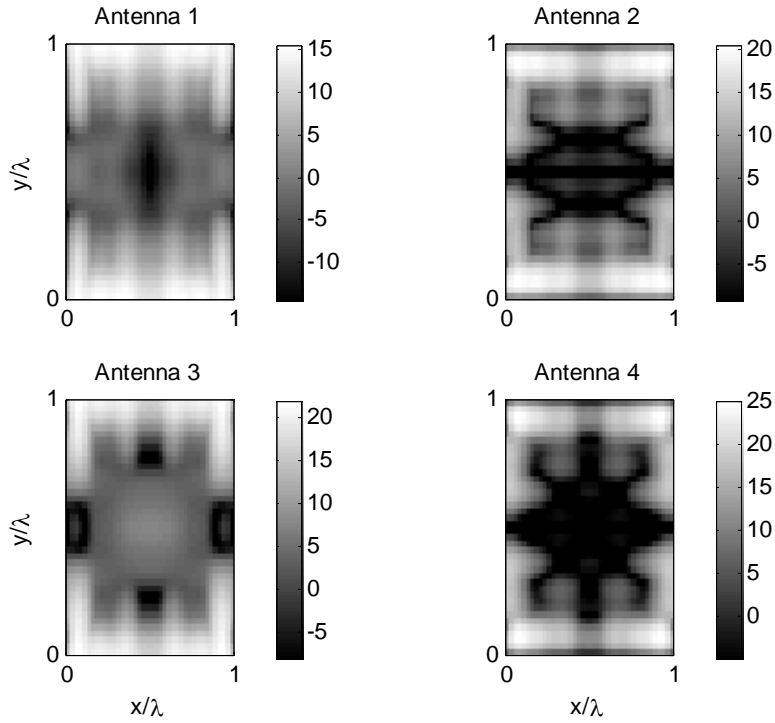


Figure 38: Magnitude (dB) of the optimal four current distributions for an environment described by a Laplacian power angular spectrum and a radiation efficiency of 99%.

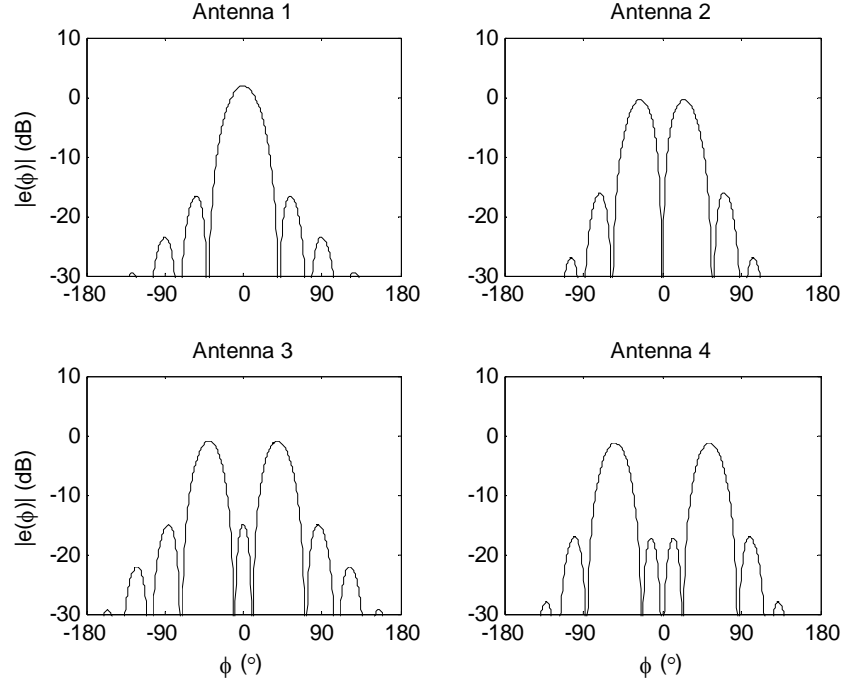


Figure 39: Optimal four radiation patterns for an environment described by a Laplacian power angular spectrum and a radiation efficiency of 99%.

## Conclusions

This report has summarized the key results in a number of areas pertinent to the development of new ad hoc networking technologies for mobile networks that employ multiple transmit and receive antennas. Notable advances have been made in numerous areas and are described in detail in the technical papers referenced in Appendix 3. Although it is hard to summarize the results of a research effort with such a large scope of activity concisely, it is clear that significant advances have been made since this project was initiated three years ago. The work on network routing and scheduling is developing more sophisticated tools to include physical layer information, allow cooperative relaying, multi-packet reception and other features. There are also significant advances in defining appropriate channel models for mobile, multi-user MIMO ad hoc networks and this in turn is resulting in effective and realistic feedback control between the transmitter and receiver, improved channel state estimation, interference suppression, beamforming and diversity combining techniques. These effects combine to enable an improved capability to design cross-layer scheduling and routing algorithms that exploit MIMO spatial multiplexing and diversity gains to achieve end-to-end performance improvements in mobile ad hoc networks.



# Appendices

## *Appendix 1: Honors and Awards*

### Garcia-Luna-Aceves

- Best Paper Award: X. Wu, H. Sadjadpour and J.J. Garcia-Luna-Aceves, ``Analytical Modeling of Link and Path Dynamics and Their Implications on Packet Length in MANETs," *Proc. SPECTS 2007: 2007 Int'l Symposium on Performance Evaluation of Computer and Telecommunication Systems*, San Diego, CA, July 16--18, 2007.
- Best Paper Award: J. Boice, J.J. Garcia-Luna-Aceves, and K. Obraczka, ``On-demand Routing in Disrupted Environments," *Proc. IFIP Networking 2007*, Atlanta, GA, May 14--18, 2007.
- Conference Organization: Technical Program Committee (TPC) member for ACM Annual International Conference on Mobile Computing and Networking (MOBICOM) 2007 and IEEE Infocom 2007.

### Hua

- Member of Advisory Board, International Conference on Information, Communications and Signal Processing, Singapore, 10-13 December 2007.
- Member of Advisory Board, IEEE First International Workshop on Wireless Mesh and Ad Hoc Networks, Honolulu, Hawaii, Aug 16, 2007.
- Member of Advisory Board, WSEAS International Conference on Applied Computer Science, Tenerife, Canary Islands, Spain, Dec 16-18, 2006.
- Chair, University of California Industry University Cooperative Research Program Executive Committee for Communications and Networking, 2006 -2007.
- Member, IEEE Signal Processing Society Technical Committee on Signal Processing for Communications, 2005-2007.
- Member, IEEE Signal Processing Society Technical Committee on Sensor Array and Multi-channel Processing, 2005-2007.
- Member of Editorial Board, IEEE Signal Processing Magazine, 2007 – 2009.
- Editor, EURASIP Journal: Signal Processing, 2005-2008.
- Member of Technical Committee, IEEE Workshop on Signal Processing Advances in Wireless Communications, Helsinki, Finland, June 17-20, 2007.
- Member of Technical Committee, IEEE Globecom 2007 Ad-hoc and Sensor Networking Symposium

- Member of Technical Committee, IEEE Globecom 2007 Signal Processing Symposium.
- Member of Technical Committee, International Conference on Body Area Networks, May 14-16, 2007.
- Member of Technical Committee, CHINACOM 2006, Beijing, China, Oct. 16-19, 2006.
- Member of Technical Committee, EUSIPCO 2006, Florence, Italy, Sept 4-8, 2006.
- Chair, Session of Cooperative Networks, IEEE ICASSP, Honolulu, HI, April 2007.

### **Jafarkhani**

- School of Engineering Fariborz Maseeh Best Faculty Research Award, 2007.
- Listed as a highly cited researcher in <http://www.isihighlycited.com>
- Area Editor, IEEE Transactions on Wireless Communications.
- Session chair in following conferences:  
IEEE Global Communications Conference (Globecom), 2006.  
IEEE Wireless Communications and Networking Conference (WCNC), 2007.  
IEEE Data Compression Conference (DCC), 2007.
- TPC member in following conferences:  
IEEE Global Communications Conference (Globecom), 2007.  
IEEE Wireless Communications and Networking Conference (WCNC), 2007.

### **Jensen**

- Invited Keynote Address: *2007 International Symposium on Antennas and Propagation, Niigata, Japan*
- 2 Invited Conference Presentations
- IEEE Antennas and Propagation Society Administrative Committee (elected member): 3 year term 2005-2007
- Symposium General Co-Chair, 2007 IEEE Antennas and Propagation Society International Symposium, Honolulu, HI
- Editor, *IEEE Transactions on Antennas and Propagation*, 2003-present
- IEEE Antennas and Propagation Joint Meetings Committee Member, 2002-Present

### **Krishnamurthy**

- IEEE Career Awards:  
IEEE Senior Member 2007
- Conference Organization
  - a. Technical Program Committee (TPC) Vice-Chair for ACM Annual International Conference on Mobile Computing and Networking (MOBICOM) 2007
  - b. TPC Co-Chair for IEEE Communications Society Conference on Sensor, Mesh and Ad hoc Communications and Networks (SECON) 2008
  - c. Area TPC Chair -- IEEE INFOCOM 2008
- IEEE Editorial Assignments:
  - a. Editorial Board of the "IEEE Transactions on Mobile Computing"
  - b. Associate Editor-in-Chief for ACM Mobile Computing and Communications Review (MC2R)
  - c. Editorial Board for Ad hoc Networks Journal (Elsevier Publications)

### **Milstein**

- Senior Editor, IEEE Journal on Selected Areas in Communications
- Editorial Board, Journal of the Franklin Institute

### **Proakis**

- Athanasios Papoulis Award received on September 6, 2007, from the European Signal Processing Society "For Outstanding Contributions to Education in the Signal Processing Discipline."
- Guest Co-Editor of IEEE JSAC Special Issue on Equalization Techniques for Wireless Communications – Theory and Applications.
- Member of the IEEE Richard W. Hamming Medal Committee
- 2007 European Signal Processing Conference (EUSIPCO), Chair of Session on Channel Modeling, Estimation and Equalization, September 6, 2007, Poznan, Poland.
- Best Student Paper Award, IEEE Personal, Indoor, and Mobile Radio Conference, September 2006, (with Tiejun Wang and James Zeidler).

### **Swindlehurst**

- Paper Award  
Awarded the 2006 IEEE Communications Society Stephen O. Rice Prize in the Field of Communications Theory for the two-part paper "A Vector-Perturbation Technique for Near-Capacity Multi-antenna Multi-user Communication," which appeared in the *IEEE Transactions on Communications*, January and March, 2005, co-authored with Dr. Christian Peel (ArrayComm LLC) and Dr. Bert Hochwald (Beceem, Inc).

- Conference Organization  
Technical Program Chair for 2008 *IEEE International Conference on Acoustics, Speech and Signal Processing*.
- IEEE Editorial Assignments:  
Editor-in-Chief, *IEEE Journal of Selected Topics in Signal Processing*  
b. Member, Editorial Board, *IEEE Signal Processing Magazine*  
c. Member, Editorial Board, *EURASIP Journal of Wireless Communications and Networking*

### **Zeidler**

- Best Student Paper Award, IEEE Personal, Indoor, and Mobile Radio Conference, September 2006. (with Tiejun Wang and John Proakis)
- Guest Editor, IEEE Signal Processing Special Issue on “Signal Processing for Wireless Ad Hoc Networks”, September 2006

### **Zorzi**

- IEEE Fellow, 2007
- Editor for Europe of the Wiley Journal on Wireless Communications and Mobile Computing
- Member of the editorial board: ACM Journal of Wireless Networks, IEEE Transactions on Wireless Communications, IEEE Transactions on Communications. Elsevier’s Journal of Ad Hoc Networks
- Member of the steering committee: IEEE Transactions on Mobile Computing
- Guest editor: “Cognitive wireless networks,” IEEE Wireless Communications Magazine (Aug. 2007), “Energy Efficient Design in Wireless Ad Hoc and Sensor Networks,” Elsevier’s Journal of Ad Hoc Networks (scheduled for 4Q 2007); “MIMO-Optimized Transmission Systems for Delivering Data and Rich Content,” IEEE JSTSP (scheduled for 2008); “Underwater communications and Wireless Networks,” IEEE JSAC (scheduled for 4Q 2008).
- Conference organizing committee: Technical Program co-Chair, IEEE SECON 2006 (Sep. 2006), Technical Program co-Chair, ACM WUWNet 2007.
- Best paper awards: IEEE CAMAD, June 2006.
- Best paper award nomination: ACM IWCMC, July 2006.
- Paper award nomination: COMSOC best tutorial paper, 2007

## ***Appendix 2: Patents and Technology Transfers***

### **Technology Transfer**

Professors Jensen and Swindlehurst have patent-pending work on the use of space-time coding to allow dual-antenna transmission from maneuvering air vehicles continues to move forward. The problem this addresses is the data link loss that occurs when the vehicle-mounted antenna is occluded by the airframe during a maneuver. Use of appropriate space-time codes with dual antennas allows communication to occur for any vehicle attitude. They have constructed a prototype system that will undergo testing by the US Air Force (Edwards AFB) in real-time flight testing during the 2007-2008 academic year. This work is funded by the State of Utah and the US Department of Defense through the Central Test and Evaluation Investment Program (CTEIP).

BYU has collaborated with the San Diego Research Corporation (SDRC) to develop prototype real-time MIMO communications systems, with the work being funded by DARPA. They have also collaborated with SDRC to demonstrate the use of robotic relays to overcome the shadowing effects in urban environments. Finally, Professor Jensen is working with Rayspan Corporation, a start-up company with venture capital funding, to develop miniature antenna technologies for use in WLAN systems.

From July, 2006, to June 2007, Professor Swindlehurst was on leave from BYU, working as the Vice-President of Research at ArrayComm LLC in San Jose, CA. During this time, he was responsible for all research activities at ArrayComm, including new algorithm development, testing, software implementation and recruiting. He managed a staff of 17 engineers working on advanced techniques for MIMO wireless communications, channel estimation, equalization, interference cancellation in various wireless protocols including 802.16e (WiMAX), 3GPP HSDPA (High Speed Data Packet Access), PHS, GSM, S-DMB, etc. This was a valuable experience both in terms of learning about the requirements of real wireless networks, and in applying advanced techniques to real-world problems. Professor Swindlehurst has now assumed a new academic position at the University of California, Irvine where he continues his research on this MURI research effort.

## ***Appendix 3: Publications***

### **Appendix 3a: Published Journal Publications**

#### **Zorzi, Zeidler, Swindlehurst, Jensen, Krisnamurthy, Rao and Proakis**

- M. Zorzi, J. Zeidler, A. Anderson, A. L. Swindlehurst, M. Jensen, S. Krishnamurthy, B. Rao, J. Proakis; "Cross-Layer Issues in MAC Protocol Design for MIMO Ad Hoc Networks"; IEEE Wireless Communications Magazine (special issue on smart antennas), Vol. 13, no. 4, pp. 62-76, August, 2006

### **Hua and Swindlehurst**

- Yue Rong, Yingbo Hua, Ananthram Swami, A. Lee Swindlehurst, "Space-Time Power Schedule for Distributed MIMO Links Without Instantaneous Channel State Information at Transmitting Nodes," accepted for publication in *IEEE Transactions on Signal Processing*.

### **Milstein and Proakis**

- P. Amihood, E. Masry, L. B. Milstein, J. G. Proakis, "Performance Analysis of a Pre-BLAST DFE Technique for MISO Channels with Decentralized Receivers," *IEEE Transactions on Communications*, vol. 55, pp. 1385-1396, July 2007.
- P. Amihood, E. Masry, L.B. Milstein, J.G. Proakis, "Performance Analysis of High Data Rate MIMO Systems in Frequency Selective Fading Channels", accepted for publication in *IEEE Transactions on Information Theory*.

### **Zeidler and Proakis**

- J. Jootar, J. R. Zeidler, and J. G. Proakis, "Performance of Convolutional Codes With Finite-Depth Interleaving and Noisy Channel Estimates," *IEEE Transactions on Communications*, vol. 54, pp. 1775-1786, October 2006.
- J. Jootar, J. R. Zeidler, and J. G. Proakis, "On the Performance of Closed-Loop Transmit Diversity with Noisy Channel Estimates," *IEEE Transactions on Communications*, in press, 2007.
- J. Jootar, J. R. Zeidler, and J. G. Proakis, "On the Performance of Concatenated Convolutional Code and Alamouti Space-Time Code with Noisy Channel Estimates and Finite Depth Interleaving," *IEEE Transactions on Communications*, in press, 2007.

### **Haykin**

- Arsaraatnaam, S. Haykin, and R.J. Elliott, "Discrete -time nonlinear filtering algorithms using Gauss-Hermite quadrature," *Proc. IEEE*, vol.95, pp. 953-977, May 2007.
- N. Costa, S. Haykin, "A novel wideband MIMO channel model and experimental validation," Accepted for publication in *Trans. Antennas and Propagation*.

### **Hua**

- K. Hong and Y. Hua, "Throughput analysis of large wireless networks with regular topologies," *EURASIP Journal on Wireless Communications and Networking*, Vol. 2007 (2007), Article ID 26760, 11 pages.

### **Jafarkhani**

- L. Liu and H. Jafarkhani, "Space Time Trellis Codes Based on Channel Phase Feedback," *IEEE Transactions on Communications*, vol. 54, pp. 2186-2198, Dec 2006.
- L. Liu and H. Jafarkhani, "Novel Transmit Beamforming Schemes for Time-Selective Fading Multiantenna Systems," *IEEE Transactions on Signal Processing*, vol. 54, pp. 4767-4781, Dec 2006.

- L. Liu and H. Jafarkhani, "Successive Transmit Beamforming Algorithms for Multiple-Antenna OFDM Systems," *IEEE Transactions on Wireless Communications*, vol. 6, pp. 1512-1522, Apr. 2007.

### **Javidi**

- J. Price and T. Javidi, "Decentralized Rate Assignments in a Multi-Sector CDMA Network," *IEEE Transactions on Wireless Communications*, Vol. 5, No. 12, 2006
- S. Kittipiyakul and T. Javidi, "Resource allocation in OFDMA with time-varying channel and bursty arrivals," Accepted for publication in *IEEE Communications Letters*.
- J. Price and T. Javidi, " Leveraging Downlink for Efficient Uplink Allocation in a Single-Hop Wireless Network," To Appear in *IEEE Transactions on Information Theory*.
- S. Kittipiyakul and T. Javidi, "Optimal operating point for MIMO multiple access channel with bursty traffic," Accepted for publication in *IEEE Transactions on Wireless Communication*.
- J. Price and T. Javidi, "Distributed Rate Assignments for Simultaneous Interference and Congestion Control in CDMA-Based Wireless Networks," to appear in *IEEE Transactions on Vehicular Technology*.

### **Jensen**

- J. W. Wallace and M. A. Jensen, "Time varying MIMO channels: measurement, analysis, and modeling," *IEEE Trans. Antennas Propag., Special Issue on Wireless Communications*, vol. 54, pp. 3265-3273, Nov. 2006.
- M. A. Jensen, M. D. Rice, and A. L. Anderson, "Aeronautical telemetry using multiple-antenna transmitters," *IEEE Trans. Aerospace Electronic Systems*, vol. 43, pp. 262-272, Jan. 2007.
- N. W. Bikhazi and M. A. Jensen, "The relationship between antenna loss and superdirectivity in MIMO systems," *IEEE Trans. Wireless Communications*, vol. 6, pp. 1796-1802, May 2007.
- J. W. Wallace, M. A. Jensen, A. Gummalla, and H. Lee, "Experimental characterization of the outdoor MIMO wireless channel temporal variation," *IEEE Trans. Vehicular Technology*, vol. 56, pp. 1041-1049, May 2007.
- K. F. Warnick and M. A. Jensen, "Optimal noise matching for mutually-coupled arrays," *IEEE Trans. Antennas and Propagation*, vol. 55, pp. 1726-1731, June 2007.
- S. Wang, A. Abdi, J. Salo, H. El-Sallabi, J. Wallace, P. Vainikainen, M. A. Jensen, "Time-varying MIMO channels: parametric statistical modeling and experimental results," *IEEE Trans. Vehicular Technology*, vol. 56, pp. 1949-1963, July 2007.

### **Krishnamurthy**

- G. Jakllari, S. V. Krishnamurthy, M. Faloutsos, and P. Krishnamurthy, "On Broadcasting with Cooperative Diversity in Multi-hop Wireless Networks", *IEEE Journal on Selected Areas on Communications*, vol. 25, issue 2, pages 484-496, February 2007.
- G. Jakllari, W. Luo, S. V. Krishnamurthy, "An Integrated Neighbor Discovery and MAC Protocol for Ad Hoc Networks Using Directional Antennas", *IEEE Transactions on Wireless Communications*, vol.6, issue 3, pages 1014-1024, March 2007.
- G. Jakllari, S. V. Krishnamurthy, M. Faloutsos, P. Krishnamurthy and Ozgur Ercetin, "A Cross-Layer Framework for Exploiting Virtual MISO Links in Mobile Ad hoc Networks", *IEEE Transactions on Mobile Computing*, vol. 6, issue 6, pages 579-594, June 2007.

### **Milstein**

- D. Piazza, L.B. Milstein, "Analysis of Multiuser Diversity in Time-Varying Channels." Accepted in *IEEE Transactions on Wireless Communications*.
- A. Ling and L.B. Milstein, "Tradeoff Between Diversity and Channel Estimation Errors in Asynchronous MC-DS-CDMA and MC-CDMA", accepted for publication in *IEEE Transactions on Communications*.

### **Rao**

- J. Zheng, E. Duni, and B. D. Rao, "Analysis of multiple antenna systems with finite-rate feedback using high resolution quantization theory," *IEEE Trans. on Signal Processing*, Apr. 2007.
- J. Zheng and B. D. Rao, "Analysis of multiple antenna systems with finite-rate channel information feedback over spatially correlated fading channels," to appear in *IEEE Trans. on Signal Processing*, October, 2007.

### **Swindlehurst**

- Christian Peel and A. Lee Swindlehurst, "Throughput-Optimal Training for a Time-Varying Multi-Antenna Channel," accepted for publication in *IEEE Transactions on Wireless Communications*.

### **Zeidler**

- Haichang Sui and James R. Zeidler, "A Robust Coded MIMO FH-CDMA Transceiver for Mobile Ad Hoc Networks," *IEEE Journal on Selected Areas in Communications* (special issue on Optimization of MIMO Transceivers for Realistic Communication Networks), September 2007. In press.

### **Zorzi**

- M. Levorato, S. Tomasin, P. Casari, and M. Zorzi, "Physical Layer Approximations for Cross-Layer Performance Analysis in MIMO-BLAST Ad Hoc Networks," *IEEE Transactions on Wireless Communications*, accepted for publication.



- Marco Levorato, Stefano Tomasin, and Michele Zorzi, "Cooperative spatial Multiplexing for Ad Hoc Networks with Hybrid ARQ: Design and Performance Analysis", *IEEE Transactions on Communications*, accepted for publication.

## **Appendix 3b: Submitted Journal Publications**

### **Cruz and Milstein**

- Y.Nebat, R. Cruz and L.B. Milstein, "On Path Selection Based Decode and Forward Relaying For Cooperative Diversity", submitted to the *IEEE Transactions on Information Theory*.

### **Milstein and Proakis**

- P. Amihoud, E. Masry, L. B. Milstein, J. G. Proakis, "The Effects of Channel Estimation Errors on a Nonlinear Precoder for MISO Channels with Decentralized Receivers," submitted to *IEEE Transactions on Communications*, August 2007.

### **Swindlehurst and Hua**

- Matthew Nokleby, A. Lee Swindlehurst, Yue Rong, and Yingbo Hua, "Cooperative Power Scheduling for Wireless MIMO Networks," submitted to *IEEE Journal on Selected Areas in Communications*, July, 2007.

### **Zeidler and Jensen**

- A. L. Anderson, J. R. Zeidler, and M. A. Jensen, "Stable transmission in the time-varying MIMO broadcast channel," submitted to special issue MIMO Transmission with Limited Feedback, EURASIP 2007.

### **Hua**

- B. Zhao and Y. Hua, "Distributed medium access for a large wireless mesh network with multiple antenna elements on each node," *IEEE Transactions on Wireless Communications*, submitted, Dec 2006.
- K. Hong, Y. Hua and A. Swami, "Distributed and cooperative link schedule for large-scale multi-hop wireless networks," *EURASIP Journal on Wireless Communications and Networking*, submitted May 8, 2007.
- Y. Rong and Y. Hua, "Fairness and QoS based space-time power scheduling of MIMO links", *IEEE J. Selected Topics in Signal Processing*, submitted, July 12, 2007.

### **Jafarkhani**

- S. Ekbatani and H. Jafarkhani, "Combining Beamforming and Space-Time Coding Using Quantized Feedback," submitted to *IEEE Trans. on Wireless Communications*.

### **Jensen**

- B. T. Maharaj, J. W. Wallace, and M. A. Jensen, “A low-cost open-hardware wideband multiple-input multiple-output (MIMO) wireless channel sounder,” submitted to *IEEE Trans. Instrum. Meas.*, Mar. 2006.
- N. W. Bikhazi and M. A. Jensen, “Impact of coupling on MIMO capacity in correlated fast fading environments,” submitted to *IEEE Trans. Antennas Propag.*, Jun. 2006.
- M. A. Jensen and J. W. Wallace, “Capacity of the continuous-space electromagnetic channel,” submitted to *IEEE Trans. Antennas Propag.*, Aug. 2006.
- D. Pinchera, J. W. Wallace, M. D. Migliore, and M. A. Jensen “Experimental analysis of a wideband adaptive-MIMO antenna,” submitted to *IEEE Trans. Antennas Propag.*, Dec. 2006.
- N. W. Bikhazi and M. A. Jensen, “Optical MIMO using square-law detection,” submitted to *IEEE Trans. Communications*, Jan. 2007.
- M. A. Jensen and J. W. Wallace, “Antennas for SIMO/MIMO Communication Systems,” to appear in *Modern Antenna Handbook*, C. A. Balanis, Ed., John Wiley & Sons, 2007.
- J. W. Wallace and M. A. Jensen, “Electromagnetic considerations for communicating on correlated MIMO channels with covariance information,” submitted to *IEEE Trans. Wireless Communications*, Dec. 2005.

### **Milstein**

- T. Srikanth, K. Vishnu Vardhan, A. Chockalingam, L. B. Milstein, “Improved Linear Parallel Interference Cancellers.” Submitted to *IEEE Transactions on Wireless Communications*.
- Q. Qu, L. B. Milstein, D. R. Vaman, “Cognitive Radio-Based Multi-User Resource Allocation in Mobile Ad Hoc Networks Using Multicarrier Modulation.” Submitted to *IEEE Journal on Selected Areas in Communications*.
- Q. Qu, L. B. Milstein, D. R. Vaman, “Cross-Layer Distributed Power Control and Scheduling for Delay-Constrained Applications over CDMA-Based Wireless Ad-Hoc Networks.” Submitted to *IEEE Transactions on Communications*.

### **Rao**

- Y. Isukapalli, R. Annavajjala, and B. D. Rao, “Performance analysis of transmit beamforming for MISO systems with imperfect feedback,” *IEEE Trans. on Communications*. submitted 12-Jun-2006, revised 08-Feb-2007.
- J. Zheng and B.D. Rao, “Analysis of Vector Quantizers Using Transformed Codebooks with Application to Feedback-Based Multiple Antenna Systems,” submitted to *EURASIP wireless communications and networking*, March 2007.

- J. Zheng and B.D. Rao “Capacity Analysis of MIMO Systems using Limited Feedback Transmit Precoding Schemes,” submitted to *IEEE Transactions on Signal Processing*, Revised July 2007.

### **Swindlehurst**

- Zhu Han, A. Lee Swindlehurst, and K. J. Ray Liu, “Optimization of MANET Connectivity via Smart Deployment/Movement of Unmanned Air Vehicles,” submitted to *IEEE Transactions on Vehicular Technology*, July, 2007.

### **Zeidler**

- H. Sui and J. R. Zeidler, “Information Efficiency and Transmission Range Optimization for Coded MIMO FH-CDMA Ad Hoc Networks in Time-Varying Environment”, submitted to *IEEE Transactions on Communication*.

## **Appendix 3c: Conference Papers**

### **Javidi, Cruz and Milstein**

- Y. Lin, T. Javidi, R. L. Cruz and L. B. Milstein, "Distributed Link Scheduling, Power Control and Routing for Multi-hop Wireless MIMO Networks ,” Asilomar Conference on Signals, Systems, and Computers, November 2006.

### **Hua and Swindlehurst**

- Y. Rong, Y. Hua and A. L. Swindlehurst, "Space-time power schedule for distributed MIMO links without channel state information at transmitting nodes," *IEEE International Conference on Acoustics, Speech and Signal Processing*, Honolulu, Hawaii, April 2007.

### **Milstein and Proakis**

- P. Amihoud, E. Masry, L. B. Milstein, J. G. Proakis, “Analysis of a MISO Pre-BLAST-DFE Technique for Decentralized Receivers," in *Proc. of the 40th Asilomar Conference on Signals, Systems and Computers*, Pacific Grove, CA, USA, October 29 - November 1, 2006.

### **Proakis and Zeidler**

- Kostas Stamatiou, John G. Proakis and James R. Zeidler, “Information efficiency of ad hoc networks with FH-MIMO Transceivers,” *Proceedings of the IEEE International Conference on Communications*, Glasgow, Scotland. June 2007.
- K, Stamatiou, J. G. Proakis and J.R. Zeidler, “Evaluation of MIMO Techniques in FH-Multi-Access Ad Hoc Networks, /*Proceedings of the IEEE Global Communications Conference*/, Washington DC, November 2007

### **Zeidler and Jensen**

- A. L. Anderson, J. R. Zeidler, and M. A. Jensen, “Performance of transmit precoding in time-varying point-to-point and multi-user MIMO channels,” *Proceedings of the 39th Asilomar Conference on Signals, Systems, and Computers*, 2006, Pacific Grove, CA, Oct. 29-Nov. 1, 2006.

### **Garcia-Luna-Aceves**

- J.J. Garcia-Luna-Aceves, H. Sadjadpour, and Z. Wang, "Challenges: Towards Truly Scalable Ad Hoc Networks," *Proc. ACM Mobicom 2007*, Montreal, QC, Canada, September 9--14, 2007.
- J.J. Garcia-Luna-Aceves, H. Sadjadpour, and Z. Wang, "Extending the Capacity of Ad Hoc Networks beyond Network Coding," *Proc. International Wireless Communications and Mobile Computing Conference (IWCMC 2007)*, Honolulu, Hawaii, August 12-16, 2007.
- X. Wang, J.J. Garcia-Luna-Aceves, and H. Sadjadpour, "Distributed Channel Access Scheduling for Ad Hoc Networks Using Virtual MIMO," *Proc. 16th IEEE International Conference on Computer Communication Networks (ICCCN 2007)*, Honolulu, Hawaii, Aug. 13--16, 2007.
- X. Wang, J.J. Garcia-Luna-Aceves, and H. Sadjadpour, "Topology Aware Hybrid Channel Access Using Virtual MIMO," *Proc. IEEE Symposium on Computers and Communication (ISCC '07)*, Aveiro, Portugal, July 1--4, 2007.
- X. Wang and J.J. Garcia-Luna-Aceves, "Election based Hybrid Channel Access," *Proc. IFIP Networking 2007*, Atlanta, GA, May 14--18, 2007.
- R. Moraes, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, "Many-to-Many Communication: A New Approach for Collaboration in MANETs," *Proc. IEEE Infocom 2007*, Anchorage, Alaska, 6--12 May 2007.

### **Haykin**

- N. Costa, S. Haykin, "A novel wideband MIMO channel model and the Wideband MIMO Software Defined Radio," *Proc. WiCOM 2006*, 22-24 Sept. 2006, pp. 1-4.
- N. Costa, S. Haykin, "A novel wideband MIMO channel model and McMaster's Wideband MIMO SDR," *Proc. ACSSC 2006*, Oct-Nov 2006, pp. 956-960.

### **Hua**

- B. Zhao and Y. Hua, "A distributed MAC scheme for large network of wireless routers," *Army Science Conference*, Orlando, Florida, Nov 27-30, 2006.
- Y. Rong and Y. Hua, "Optimal power schedule for distributed MIMO links," *Army Science Conference*, Orlando, Florida, Nov 27-30, 2006.
- B. Zhao and Y. Hua, "Distributed medium access for a large wireless mesh network with multiple antenna elements on each node," *IEEE ICASSP*, Honolulu, Hawaii, April 2007.

### **Jafarkhani**

- S. Ekbatani and H. Jafarkhani, "Space-Time Coding and Beamforming Using Noisy Rate-Limited Feedback," *Asilomar Conference on Signals, Systems, and Computers*, Nov. 2006.

- S. Ekbatani, F. Etemadi, and H. Jafarkhani, "Transmission Over Slowly Fading Channels Using Unreliable Quantized Feedback," IEEE Data Compression Conference (DCC-07), Mar. 2007.
- Y. Jing and H. Jafarkhani, "Network Beamforming Using Relays with Perfect Channel Information," IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP-07), Apr. 2007.
- F. Etemadi and H. Jafarkhani, "Joint Source-Channel Coding for Quasi-Static Fading Channels with Quantized Feedback," IEEE International Symposium on Information Theory (ISIT 2007), July 2007.
- F. Etemadi, S. Ekbatani, and H. Jafarkhani, "Joint Source-Channel Coding for Quasi-Static Fading Channels with Noisy Quantized Feedback," IEEE Information Theory Workshop (ITW 2007), Sept. 2007.
- S. Ekbatani, F. Etemadi, and H. Jafarkhani, "Outage Behavior of Quasi-Static Fading Channels with Partial Power Control and Noisy Feedback," IEEE Global Communications Conference (Globecom-07), Nov. 2007.

### **Javidi**

- P. Elia, S. Kittipiyakul, and T. Javidi, "Cooperative Diversity in Wireless Networks with Stochastic and Bursty Traffic," ISIT'07, June 2007.
- P. Elia, S. Kittipiyakul, and T. Javidi, "On the Responsiveness-Diversity-Multiplexing Tradeoff," WiOpt'07, April 2007.
- D. Klein, P. Lee, K. Morgansen and T. Javidi, "Integration of Communication and Control using Discrete Time Kuramoto Models for Multivehicle Coordination over Broadcast Network," to appear in IEEE Conference on Decision and Control, Dec 2007.
- D. Lim, J. Shim, T. Simunic Rosing, and T. Javidi, "Scheduling Data Delivery in Heterogenous Wireless Sensor Networks," IEEE International Symposium on Multimedia, December 2006.
- J. Price and T. Javidi, "Leveraging Downlink for Regulation of Distributed Uplink CDMA," IEEE Globecom Conference, December 2006.
- J. Price and T. Javidi, "Leveraging Downlink for Optimal Uplink Allocation: An Incentive Compatible Approach," Asilomar Conference on Signals, Systems, and Computers, November 2006.
- T. Javidi, "Cooperation and Resource Sharing in Data Networks: A Delay Perspective," Allerton Conference on Communication, Control, and Computing, October 2006.

- S. Kittipiyakul and T. Javidi, "Optimal operating point in MIMO channel for delay-sensitive and bursty traffic," *ISIT'06*, July 2006.

### **Jensen**

- D. Pinchera, M. D. Migliore, M. A. Jensen, and J. W. Wallace, "Characterization of a wideband adaptive-MIMO antenna," *2007 IEEE AP-S International Symposium Digest*, Honolulu, HI, June 10-15, 2007.
- B. T. Quist and M. A. Jensen, "Optimal antenna pattern design for MIMO systems," *2007 IEEE AP-S International Symposium Digest*, Honolulu, HI, June 10-15, 2007.
- K. F. Warnick and M. A. Jensen, "Optimal noise matching condition for mutually coupled antenna arrays," *2007 IEEE AP-S International Symposium Digest*, Honolulu, HI, June 10-15, 2007.
- H. Stephen and M. A. Jensen, "Optimizing diversity gain using uncoupled impedance matching with coupled antennas," *2007 IEEE AP-S International Symposium Digest*, Honolulu, HI, June 10-15, 2007.
- J. W. Wallace and M. A. Jensen, "Modeling antenna coupling and correlation in rapidly fading MIMO channels," *Proceedings of 2006 European Conference on Antennas and Propagation*, Nice, France, Nov. 6-10, 2006.
- M. A. Jensen and B. Booth, "Optimal uncoupled impedance matching for coupled MIMO arrays," *Proceedings of 2006 European Conference on Antennas and Propagation*, Nice, France, Nov. 6-10, 2006.
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